A case study investigating the impacts of coagulants on taste and odour reduction in drinking water

A thesis submitted in fulfilment of the requirements for the degree of Master of Engineering

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis/project is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed. I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

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Summary

Goulburn Valley Water (GVW) is a regional water business that provides water and waste water services to 54 towns across 20,000 km^2 in Northern Victoria. Taste and odour issues across the region resulted in this case study to investigate improvements through optimisation of existing treatment processes.

Historically, Euroa has had problems with taste and odour although, there are limited numbers of formal complaints recorded in widespread locations across the town. A Taste and Odour Panel determined the key odours in the reticulation system were earthy /musty and chlorine, with the panel unable to determine any specific tastes. The free chlorine residual at the point of entry to the reticulation system, which is consistently above the Australian Drinking Water Guidelines aesthetic limit for chlorine, was the cause of the chlorine odours detected.

Odours detected by the panel in reticulated water samples were correlated against water quality parameters. These showed there were some relationships between the identified odours and specific ultraviolet absorbance (SUVA). In addition, the level of free chlorine residual at the point of disinfection and at the outlet of the clear water storage was related to the number of chlorine and earthy /musty odours detected. As the odours appeared to be related to the levels of natural organic matter (NOM) within the source water, its removal through optimisation of the existing process and the use of alternative chemicals was investigated.

The existing water treatment plant (WTP) operation was reviewed for NOM removal and the coagulant dose optimised. Ferric sulphate and aluminium chlorohydrate (ACH) were trialled as alternative coagulants as these traditionally have a higher affinity for dissolved organic carbon (DOC) removal than aluminium sulphate currently in use.

The SUVA values seen at Euroa WTP indicate that the removal pathway for organic matter is predominantly through coagulation. Jar tests were completed to optimise the existing coagulant dose rate as well as the investigation into the alternative coagulants.

The following key points were determined from the jar tests:

- Ferric sulphate results were as expected showing a greater average DOC removal than the other samples (72 %);
- ACH provided lower than expected DOC removal rates (59 %);
- Aluminium sulphate gave consistent average DOC removal results for both the jar test and the WTP (55 % and 57 %, respectively).

Odour testing was completed following jar tests using the original taste and odour panel. The Chi squared statistic was used to calculate the expected values based on the observed odours. The following key points were determined from the odour testing results:

- The number of earthy /musty odours detected decreased against the expected value when using ACH and the number of no odour detections were greater than the expected value;
- The number of other odour detects were greater than the expected value when using ferric sulphate, however there were fewer earthy /musty odours detected than the expected value;
- The number of earthy /musty odours were greater than the expected values from the WTP samples;
- The number of earthy /musty odours were equal to the expected value for the aluminum sulphate sample.

Optimisation of the aluminium sulphate coagulation for organics removal did not appear to reduce the number of earthy /musty odours detected. The use of ferric sulphate or ACH would improve the odour of the final water at Euroa WTP.

A triple bottom line (TBL) assessment was completed to assess the economic, social and environmental impacts of each of the coagulants compared with the current practice.

The cost of treatment was determined based on jar test results, the cost of sludge disposal and the impact on the GVW infrastructure program was reviewed. The key findings associated with the economic assessment are as follows;

- The use of ACH would provide a saving of $6,345 per annum based on chemicals and $2,581 per annum based on sludge disposal costs, with the potential to defer $1.1 million in capital expenditure;
- The use of ferric sulphate would provide an increase of $9,796 per annum based on chemicals and $526 per annum based on sludge disposal costs, with no impact on the infrastructure program;
- The optimisation of aluminium sulphate coagulation would provide a saving of $3,380 per annum based on chemicals and $90 per annum based on sludge disposal costs, with no impact on the infrastructure program.

The environmental impacts of each chemical were assessed based on their potential offsite impacts. The potential for sending waste sludge to landfill was assessed as well as the potential carbon emissions associated with the delivery of chemical coagulants. The key findings from the environmental assessment are as follows:

- The use of ferric sulphate produced the most sludge therefore creating a greater volume of waste to be sent to landfill;
- The use of ACH created minimal sludge and therefore has a lower landfill potential;

- Optimisation of the aluminium sulphate coagulation created slightly less sludge than the WTP, therefore had a slightly lower landfill potential;
- Ferric sulphate and ACH dose rates were lower than the aluminum sulphate and WTP dose rates therefore requiring fewer deliveries (ferric sulphate 5, ACH 2 deliveries respectively) across the year;
- The aluminum sulphate and current WTP chemical delivery requirements were considered to be the same (7 deliveries each based on 10,000 L deliveries);
- For pH correction there was no difference in the requirements for ferric sulphate and the current operation (2 deliveries for each annually based on 10,000 L delivery);
- The ACH requires no pre pH correction therefore the post pH dosing only is required. This equated to a single chemical delivery per year.

The social impacts on the community and GVW staff were assessed based on the changes in odours. Since some residents within the Euroa connected to town water still maintain a rainwater tank for drinking purposes based on the taste and odour of the drinking water. It is assumed that with improved odour in time they would begin to use town water for drinking in preference to the rainwater. This would reduce the health risks posed by the use of rainwater tanks.

As GVW staff are integrated into the community there is a culture of informal feedback from the community to staff members. Since it is well accepted that recognition and praise are effective in motivating staff it is expected that with provision of water with improved odour there would be potential for this informal feedback to be more positive, thus increasing the motivation and pride of the staff in GVW.

The outcomes of the TBL were assessed and the key findings are as follows:

- ACH is the most attractive option across all criteria, providing economic, environmental and social benefits;
- Optimisation of aluminum sulphate coagulation has minimal financial benefits in comparison to the current WTP operation;
- Ferric sulphate has social benefits with respect to the improvement in odours. However, it is not as attractive as ACH in terms of financial and environmental aspects.

The following conclusions were made from this study:

- The predominant odours determined from the Euroa system resulted from NOM in the raw water;

- Optimisation of aluminium sulphate coagulation provides minimal social, economic and environmental benefit in comparison to the current operation.
- Ferric sulphate coagulation provides a good solution to the removal of NOM in the system, however the associated financial and environmental aspects make it less attractive than ACH;
- ACH coagulation provided the best outcome when looking at a social, economic and environmental benefits.

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Abbreviations

ABBREVIATION	DESCRIPTION
ACH	Aluminium chlorohydrate
ADWG	Australian Drinking Water Guidelines
C.t	Time of the chlorine in contact with the water
CAPEX	Capital expenditure
CHEAN	College Health Ethics Advisory Network
CWS	Clear water storage
DBP	Disinfection by products
DOC	Dissolved organic carbon
EEM	Excitation emission matrix
ESC	Essential Services Commission
FPA	Flavour profile analysis
FRI	Fluorescence regional integration (technique)
FTT	Taste/ flavour threshold test
GAC	Granular activated carbon
GHG	Greenhouse gases
GVW	Goulburn valley water
HAA	Haloacetic acid
HDPE	High density polyethylene
HOC	Hydrophobic organic carbon
LC-OCD	Liquid chromatography – organic carbon detection
LMW	Low molecular weight
MIB	2- Methylisoborneol
ML	Mega-litre
NATA	National Association of Testing Authorities, Australia
NOM	Natural organic matter
ODT	Odour detection threshold
Ofwat	Water Services Regulatory Authority (Office of Water)
OPEX	Operational expenditure
PAC	Powdered activated carbon
RAC	Regional administration centre
rpm	Revolutions per minute
SCADA	Supervisory control and data acquisition
SDWA	Safe drinking water act

SDWR	Safe drinking water regulations
SEC	Size exclusion chromatography
SEH	Science, Engineering and Health
SUVA	Specific UV absorbance
TBL	Triple bottom line
THM	Trihalomethane
TOC	Total organic carbon
TON	Threshold odour number
UV	Ultraviolet
UVA	UV absorbance
UVT	UV transmittance
WICS	Water Industry Commission of Scotland
WTP	Water treatment plant
w/w	Weight per weight
w/v	Weight per volume

1 Introduction and background information

This chapter aims to provide an introduction to the research completed starting with information regarding Goulburn Valley Water (GVW) and the importance of taste and odour in drinking water. This is followed by some further information regarding the water treatment plant (WTP) where the study took place.

Taste and odour in drinking water is important, however it is often considered as of secondary importance to water safety (Jardine, Gibson & Hrudey 1999; Doria 2010). It is widely recognised that drinking water qualities such as colour, turbidity, taste and odour are one of the customers' key measures of water supply quality with taste and odour events potentially leading to distrust of the water supplier and questions about the water safety (Jardine, Gibson & Hrudey 1999). This situation has increased the awareness of taste and odour perceptions of the customers by the water businesses.

GVW is a regional water business that provides water and waste water services to 54 towns across 20,000 km^2 in Northern Victoria. Every five years GVW submits a plan to the Essential Services Commission (ESC) detailing all planned activities and customer pricing for a five-year period. In 2013 GVW submitted their five-year water plan to the ESC for 2013 - 2018. The ESC's review of the submitted plan resulted in GVW having to provide a customer bill reduction over the five-year period. Despite this, GVW was required to retain the same capital expenditure (CAPEX) and operational expenditure (OPEX) which led to a forecasted increase in debt. In order to curtail this debt, GVW aimed to improve business efficiencies through innovation, mainly focussing on the reduction in OPEX and deferral of CAPEX. On an annual basis GVW operates a $30 million CAPEX program with around 15 % of this budget allocated to water treatment or water quality projects. The expenditure for operations and maintenance is around $26 million per annum with $1 million per annum being used for water treatment chemicals only. Approximately 50 % of all water treatment plant chemical use is in the coagulation process.

Since then planning commenced for the next five-year period (2018 – 2023) with the ESC wanting a more customer centric model for water utilities (Essential Services Commission 2016). A series of customer engagement activities by GVW showed that taste and odour is one of the areas considered to be important by the customers. Taking this into account, and previous work completed around innovation and reduction in OPEX, GVW commissioned a case study to understand how taste and odour can be improved through the optimisation of the coagulation processes. A particular aspect was to look at the economic, social and environmental aspects of using alternative coagulation chemicals at a WTP.

The case study was based in the town of Euroa (population 3500), which is situated in the Strathbogie Ranges in North Central Victoria. The WTP has the ability to source water from one of three raw water storages in the water supply system at Euroa (Figure 1). Each storage has differing water quality and characteristics. Treated water is then supplied to the townships of Euroa and Violet Town.

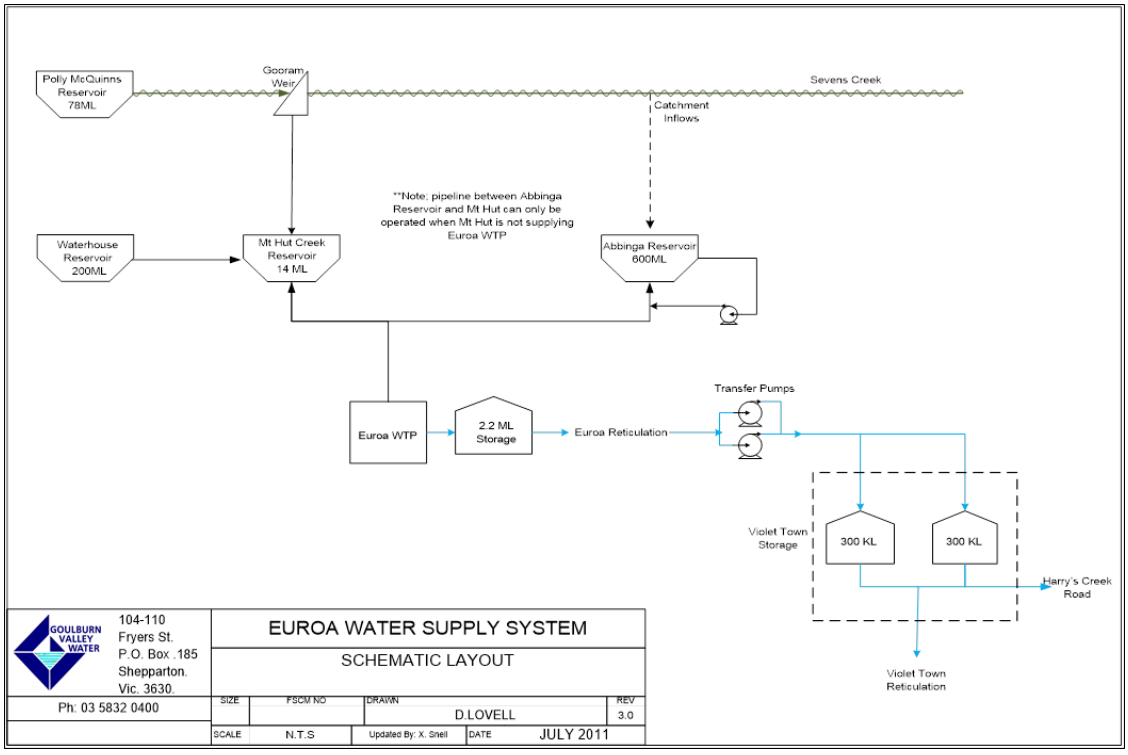


Figure 1: Schematic showing the Euroa water supply system from catchment to customer

The key questions addressed as part of this study were;

- Does optimising the water treatment plant for potential taste and odour compound and dissolved organic carbon (DOC) removal lead to an improved perception of taste and odour?
- Do specific tastes and odours relate to standard water quality parameters?
- Does the use of alternative coagulation chemicals lead to improved taste and odour perceptions?
- What are the financial impacts of optimising taste and odour removal at Euroa WTP based on the existing treatment processes?
- What are the overall financial, environmental and social benefits associated with using alternative chemicals at the Euroa WTP?

The WTP predominantly extracts water from the Mountain Hut Reservoir via a gravity pipeline, Mountain Hut Reservoir in turn is gravity fed from the Waterhouse Reservoir or from Gooram Weir.

Waterhouse Reservoir is fed from Mountain Hut Creek which is often dry. Because of this, heavy rainfall in the catchment area can significantly deteriorate water quality in a short period of time due to the deposits of organic matter into the Reservoir. It is a large deep reservoir in a predominantly forested area. There is significant vegetation around the reservoir and it has been known to have algal blooms in the summer. The storage has a high organic content and following rainfall it can experience a decrease in dissolved oxygen which has resulted in the water having prominent odours.

Gooram Weir is located on the Seven Creeks just above Gooram Falls. The Seven Creeks system is a relatively large network of smaller tributaries feeding into Seven Creeks. Polly McQuinns Dam on Seven Creeks is used to provide some water quality buffering prior to the Gooram weir.

A third off stream storage, Abbinga Reservoir (300 ML), is located below Mountain Hut Reservoir and can be used to supply the plant via Mountain Hut Reservoir. Abbinga Reservoir is used during peak summer demand to supplement low flows in the catchment or when poor water quality in Waterhouse renders it untreatable. The area of influence around Abbinga Reservoir is mixed rotational farming between sheep and annual crops.

The raw water entering the water treatment plant is from Mountain Hut Reservoir which is a mix of Waterhouse and Abbinga Reservoirs. The raw water is gravity fed to site and coagulated using aluminium sulphate, with coagulation pH adjusted using caustic soda and a flocculation aid added prior to entering a single sludge reactor clarifier. Due to the nature of the raw water, during periods of low turbidity and high colour the floc produced can be light resulting in an unstable sludge blanket. The clarifier is designed to operate with a thick sludge blanket and ideally de-sludges at the same rate at which floc is created. In the past there have been instances when the de-sludge rate has been too low and with the floc being light due to the low turbidity, the sludge blanket has risen causing floc to pass onto the filter bed. This floc deposit has then overloaded the filters placing the site at risk of protozoa breakthrough. In order to overcome this, it has become common practice for the operators to purposely overdose with coagulant. This practice increases the overall cost of treatment and can cause other issues such as elevated aluminium residuals in the reticulation system. Prior to 2015, aluminium was a scheduled item in the Victorian Safe Drinking Water Regulations (SDWR) but has subsequently been removed following a review.

Following the clarifier, the settled water is passed through two dual media filters, disinfected using chlorine gas and pH corrected using caustic soda. The treated water is stored in a 2.2 ML clear water storage (CWS) before entering the reticulation network. A schematic detailing the process can be seen in Figure 2.

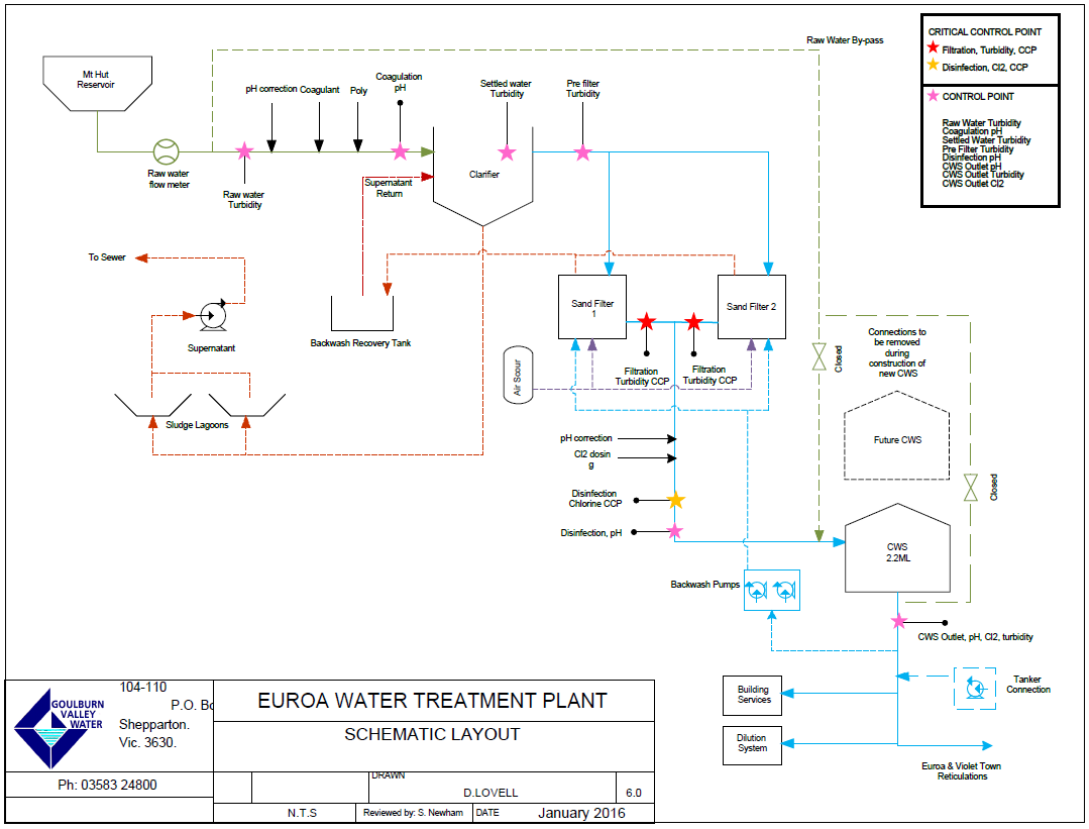


Figure 2: A schematic showing the water treatment process at Euroa WTP

Euroa WTP supplies the townships of Euroa and Violet Town. Euroa is gravity fed direct from the WTP and the water is pumped to Violet Town. The water supplied to Violet Town is re-chlorinated prior to gravity feeding into the town.

Historically, both Euroa and Violet Town have had issues with taste and odour. However there are limited numbers of formal complaints around these issues. The formal complaints show a variety of descriptors associated with the taste and odour with the complaints coming from widespread locations across the town (Figure 3). It should be noted that this figure does not take into consideration multiple complaints from the same location.

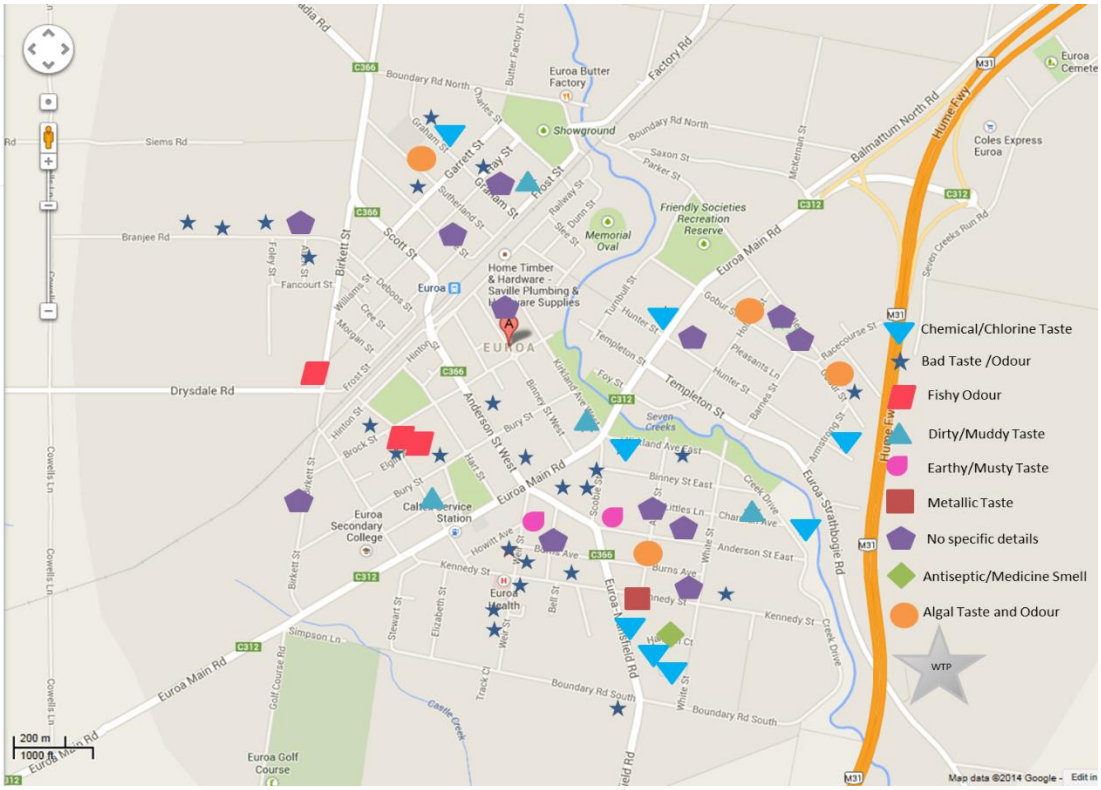


Figure 3: Taste and odour complaints mapped across the Euroa reticulation system between 2004 and 2014

The broad range of descriptors given in the formal complaints makes the identification of any underlying causes of the taste and odour difficult. Where a complaint occurs, investigation can often lead to no obvious reason for the taste and odour issue. Additional treatment such as activated carbon is regularly put in place as a mitigation measure to cope with perceived taste and odour issues, however there may be little or no obvious improvement seen in the taste or odour.

Against this background of ongoing problems and the need for cost savings, GVW undertook a case study to examine how these issues could be resolved in a cost effective manner. The next chapter considers previous studies of relevance to this issue.

2 Literature review

In this chapter previous studies related to the research were reviewed. The first Section takes into consideration customers' views of taste and odour in drinking water and their increasing role in water planning. The second Section reviews water chemistry with a particular focus on natural organic matter (NOM) and its interaction with disinfection processes. This is followed up by an appraisal of research into chemical coagulation and its optimisation for NOM removal. The final Section looks at the role of cost benefit analysis in drinking water management, and in particular, the use of Triple Bottom Line assessments as a decision making tool.

2.1 The role of the customer in taste and odour management in drinking water

Over the last decade there has been an increased interest in involving customers in the provision of drinking water (Doria 2010). The most recent example of customer involvement in drinking water management was in the United Kingdom's (U.K) 2014 pricing determination. This process put a large emphasis on customer engagement, putting the customer values at the centre of decision making as a key part of the planning process (The Water Services Regulatory Authority 2011; Water Industry Commission of Scotland 2015). In Victoria, Australia, the ESC took note of the work completed by the Water Services Regulatory Authority (Ofwat) and the Water Industry Commission of Scotland (WICS) and included similar requirements for customer engagement in the pricing determination planning process (Benvenuti 2011; Essential Services Commission 2015).

In most circumstances, customers have minimal interaction with their water supplier, tending to only contact them when there is an issue (Water Industry Commission of Scotland 2015). Past research has shown that for every formal complaint, there are around 20 people with issues who don't and although this group of people represent the majority of dissatisfied customers, there is limited research which understands the reasoning behind this (Chebat, Davidow & Codjovi 2005). Therefore, the use of customer engagement as part of the planning process for the Victorian water sector ensures the customer needs and values become integral to the ongoing performance of the water business with the aim of reducing complaints and increasing customer satisfaction (Essential Services Commission 2016).

As mentioned in Chapter 1, customers measure the service of their water supplier through the experience at their taps. Water quality parameters such as colour, turbidity, taste and odour are the key indicators to the consumer of water safety (McGuire 1995; Dietrich 2006; Doria 2010; Proulx et al. 2010). Additionally these parameters are one of the main reasons customers choose alternatives for drinking (Dietrich 2006; Doria 2006; Doria, Pidgeon & Hunter 2009;

Rodrigo, Leder & Sinclair 2009; Doria 2010). As mentioned aesthetic parameters, including the taste and odour, are normally considered by water suppliers as a secondary measure in drinking water after drinking water safety or water supply (Bruchet, Duguet & Suffet 2004). However, taste and odour in drinking water can be used to identify potential problems which may stem from issues with the raw water such as contamination or algal activity, inadequacies with the existing water treatment process, or issues with the distribution system (Watson 2004; Doria 2010). Therefore, monitoring taste and odours throughout the water treatment process allows water companies to identify where a taste and odour issue may occur and to mitigate this accordingly (Watson 2004).

A notable taste and odour event was in 1994 in the Midlands of the UK. Contamination occurred in the raw water and passed through the existing WTP without being identified. This incident resulted in causing a direct impact on 110,000 customers, however the compounds identified as being the cause were considered as having aesthetic properties only. Following the incident, a study showed there were a number of resulting psychosomatic health issues within the affected community (Fowle et al. 1996; Furness 2004). This incident resulted in the water company being prosecuted for "supplying water not fit for consumption" with the ruling judge deciding that the water was considered to be unfit if the customer did not like the taste (Furness 2004). This ruling is considered as a good reminder to water companies why taste and odour should be considered as more than an aesthetic issue and used as a critical parameter in the management of drinking water (Fowle et al. 1996; Jardine, Gibson & Hrudey 1999; Furness 2004).

2.2 Causes and removal of taste and odour in drinking water

Taste and odour in drinking water can result from a number of sources and all have the ability to impact the overall flavour of the water in different ways (Antonopoulou et al. 2014; Burlingame, Doty & Dietrich 2017). There are four basic taste sensations (salty, sweet, bitter and sour) with a fifth taste sensation (umami) more recently being recognised (Comrie et al. 2002; Dietrich 2006; Burlingame, Dietrich & Whelton 2007; Burlingame, Doty & Dietrich 2017). These tastes, in conjunction with the odour of the water, make up the overall flavour of the water which is normally what a consumer would refer to as taste (Twort, Ratnayaka & Brandt 2000; Burlingame, et al. 2017).

In the majority of cases most taste and odour issues occur from naturally occurring materials in the raw water (Suffet, Khiari & Bruchet 1999; Bae, et al. 2002; Ortenberg & Telsch 2003; Doria 2006; Burlingame, et al. 2007). Raw water quality can be changeable and is dependent on a number of factors such as weather patterns or river flows. The changeability of the raw water quality results in fleeting or inconsistent taste and odour issues. This then leads to water

companies being unable to identify the odorous compound resulting in inadequate treatment being put in place (Tondelier et al. 2008).

Where taste and odours occur in the raw water, the cause can often be traced back to land development in and around catchments. These catchments are individual ecosystems with the microbial, plant and animal life all having the ability to impact the taste and odour in the water (Twort, Ratnayaka & Brandt 2000; Dietrich 2006). Contamination of the water source may occur from both point and diffuse sources. Diffuse sources of contamination may be from soil or the geology of the area, whereas direct sources around the catchment area may include run off from surrounding land increasing plant detritus or chemical contaminants in the water (Lin 1977; Wnorowski 1992; Twort, Ratnayaka & Brandt 2000).

The decay of vegetation within catchment areas has been known to cause odours. During the decay process, a complex mixture of organic compounds is released (Lin 1977). These compounds are not only odorous in their own right but can cause the growth of other odour producing organisms such as algae which can then release odorous metabolites (Lin 1977; Wnorowski 1992; Ortenberg & Telsch 2003; Dietrich 2006)

Although there are many odorous algal metabolites, two of the most common and researched are geosmin and 2-methylisoborneol (MIB) which are released during cell lysis, most commonly from cyanobacterial blooms (Srinivasan & Sorial 2011). Both compounds are highly soluble in water and have a distinct odour. However other than their distinct odour these are not considered to be hazardous to human health (Drikas, Dixon & Morran 2009; Srinivasan & Sorial 2011; Zamyadi et al. 2015). The structures of geosmin and MIB are shown in Figure 4.

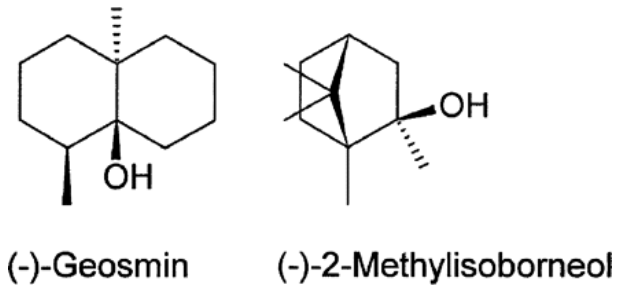


Figure 4: Chemical structures of geosmin and MIB (taken from Juttner & Watson (2007))

These compounds are known to be key causes of earthy /musty odours (Lin 1977; Wnorowski 1992; Suffet, Khiari & Bruchet 1999; Liato & Aider 2017). Although they are mostly associated with algae in drinking water, they are also present in Actinomycetes, which are a type of bacteria that are also found in soils and can influence the taste and odour of root vegetables such as beetroot (Liato & Aider 2017). The earthy /musty odours associated with

geosmin and MIB can be detected down to concentrations as low as 10 ng/L which means that there may be resultant customer complaints associated with the presence of these compounds in drinking water (Jung, Baek & Yu 2004; Drikas, Dixon and Morran 2009). Both of these compounds are difficult to remove through traditional water treatment processes with the removal efficiency being as low as 20% due to their small size (Jung, Baek & Yu 2004; Zamyadi et al. 2015). In general oxidation or adsorption are required to remove both geosmin and MIB, with the use of powdered and granular activated carbon (PAC and GAC, respectively) being a common and effective adsorbent (Drikas, Dixon and Morran 2009; Zamyadi et al. 2015). However, the presence of NOM at levels of 3- 10 mg/L DOC in water has been shown to decrease the efficiency of the removal of MIB and geosmin through adsorption onto activated carbon. This difficulty is due to the comparative size of the NOM molecules utilising the surface of the carbon in place of the smaller geosmin and MIB molecules (Srinivasan & Sorial 2011). Oxidation of geosmin and MIB is a more effective method of removal, with both geosmin and MIB being successfully removed using ozone, hydrogen peroxide (H_2O_2) or ultraviolet (UV) light, either in combination or standalone (Srinivasan & Sorial 2011; Zamyadi et al. 2015). There are disadvantages to using these as they can be expensive, associated disinfection by-products (DBPs) can form, and residual chemicals may remain within the water following oxidation which may require further removal or treatment (Srinivasan & Sorial 2011; Zamyadi et al. 2015), and some of which may also cause odours (Bruchet, Duguet & Suffet 2004).

In addition to odorous compounds being present in the raw water, organic compounds released as a result of decaying vegetation can react with disinfectants at the WTP to create odorous compounds (Bruchet, Duguet & Suffet 2004; Dietrich 2006; Deborde & van Gunten 2008; McDonald et al. 2009). In Australia the most common disinfection chemical employed is chlorine, which is also one of the most commonly cited causes of taste and odour issues with drinking water from customers (McDonald et al. 2013; McDonald et al. 2009; Piriou et al. 2004). As well as being used for pathogen control, chlorine can be used to control taste and odour compounds through oxidation, or by masking odour compounds (Bruchet, Duguet & Suffet 2004; Lin 1977). However, in the event that the control of taste and odours is not completely effective, any odours that may have been masked can recur once the free chlorine residual dissipates (Dietrich, et al. 1995; Bruchet, Duguet & Suffet 2004; Deborde & van Gunten 2008; McDonald et al. 2009). Hence, where there are variable chlorine levels within a water supply, there is the potential for taste and odour complaints to occur (Puget et al. 2010; McDonald et al. 2013).

Given the nature of taste and odour causing compounds it is expected that there are few water sources which are free from taste and odours, thus treatment will normally be required in order

to provide palatable drinking water (Wnorowski 1992; Ortenberg & Telsch, 2003; Watson 2004). Treatment of taste and odours can be difficult using traditional treatment processes (coagulation, sedimentation, filtration, chlorination) depending on the characteristics of the taste and odour causing compounds. One of the more effective approaches to the treatment of taste and odours is a multiple-barrier approach (Wnorowski 1992; Doria 2010). It can be useful to identify the taste and odour causing compounds prior to treatment, though this is not always practical or possible. Therefore, trial and error is often an appropriate method to determine the best approach when used in conjunction with odour testing through the process (Wnorowski 1992).

2.2.1 Detection of taste and odours in drinking water

The organoleptic detection of taste and odours in drinking water is subjective and the task of identifying an unacceptable level through analytical techniques for each chemical in different waters can be nearly impossible. Many taste and odour causing compounds are detectable by the human nose down to a few ng/L (Bae et al. 2002; Burlingame, Doty & Dietrich 2017). For this reason, the most common method of taste and odour detection is to use consumer and trained panels to assess drinking water flavour and odour (Doria 2010; Burlingame, Doty & Dietrich 2017).

One of the more comprehensive methods of using people (either trained or untrained) to determine tastes and odours is the Flavour Profile Analysis (FPA) technique. This technique involves the examination of the sensory characteristics to identify the full range of tastes and odours associated with each sample. Although comprehensive there is a risk that the technique may become complex, time consuming and expensive (Bartels, Burlingame & Suffet 1986; Suffet, Khiari & Bruchet 1999; Burlingame, Doty & Dietrich 2017). The most common method of detecting tastes and odour in drinking water is the Threshold Odour Number test (TON) and the Taste or Flavour Threshold Test (FTT). These methods involve the dilution of a sample to the lowest perceptible point of the taste or odour (Ortenberg & Telsch 2003; Burlingame, Doty & Dietrich 2017).

It is possible to utilise analytical testing for chemical parameters that cause odour, however this can be costly for water companies, especially where the taste and odour cause is unknown (McDonald et al. 2009). Many taste and odour causing compounds are detectable by people to below the level of detection of some analytical methods (Ortenberg & Telsch 2003; McDonald et al. 2009).

2.3 Water chemistry relating to natural organic matter

NOM is an overarching term which encompasses all organic matter present in fresh waters and can be complex in its composition (Matilainen et al. 2011). The quality of water containing

NOM is variable with no simple method to determine the overall structure of NOM (Drikas 2003). The use of simple water quality parameters can be useful to determine the characteristics and therefore the treatability of the water (Matilainen et al. 2011; Edzwald & Kaminski 2007). As the presence of NOM is the main cause of the brown colour some waters display, the use of colour as a measurement of NOM can be useful (Matilainen et al. 2011; Fan et al. 2001). Similarly, the use of absorbance of UV light at 254 nm can be a useful parameter to measure the concentration of organics present. However, the presence of other UV absorbing materials such as iron and manganese can influence the colour and are also absorbed at 254 nm which may lead to a non-representative view of the NOM present (Matilainen et al. 2011). TOC and DOC are useful for providing an overview of the entire mixture of NOM within the water source where TOC is the sum of the particulate and DOC (Matilainen et al. 2011). Although the use of all these parameters is relatively easy and can be completed fairly quickly by an operator, the disadvantage is that they only give an indication of the concentration of organics present and very little about their characteristics (Matilainen et al. 2011; Matilainen, Vespalainen & Sillanpaa 2010).

Specific UV absorbance (SUVA) can be used as an indicator of the nature of the NOM and the effectiveness of the NOM removal through coagulation (Edzwald & Tobiason 1999; Matilainen et al. 2011). SUVA is the normalisation of the ultraviolet absorbance at 254 nm (UVA) against the DOC (Edzwald & Tobiason 1999; Matilainen et al. 2011). The SUVA values may describe the nature of the NOM in water with respect to hydrophobicity, aromaticity and molecular weight as well as the potential effectiveness of NOM removal through coagulation (Tan et al. 2005; Matilainen et al. 2011).

Table 1 is taken from Edzwald and Tobiason (1999) and gives an overview of the relationship between the SUVA value, the nature of the NOM in the water and the impact on coagulation.

Table 1: A description of the nature of NOM with respect to the SUVA values and the impact on coagulation (Edzwald & Tobiason 1999)

SUVA Value	Composition	Coagulation Impact
<2	Low hydrophobicity, Low Molecular Weight	NOM has little influence on coagulation. Poor DOC removal
2 - 4	Mixture of hydrophobic and hydrophilic NOM. Mixture of molecular weights	NOM influences the coagulation. DOC removals should be good to fair
>4	High hydrophobicity and high molecular weight aromatic compounds	NOM controls coagulation. Good DOC removal

As well as giving an indication of the size and molecular weight of the organic structures present, SUVA can be used to give an indication of where DBPs will form. The reasoning for

this is that there is strong potential that aromatic structures with oxygen and nitrogen containing functional groups are the primary points of oxidation through chlorination and therefore drive the chlorine consumption (Tan et al. 2005; Ates, Kitis & Yetis 2007). In addition, research has shown that UVA was greater when humic acids were present. These humic acids tended to form higher concentrations of trihalomethanes (THMs) and haloacetic acids (HAAs) than the fulvic acids present in the same source water (Ates, Kitis & Yetis 2007).

Most water sources have a mixture of hydrophobic and hydrophilic organic content with almost half of the organic content being attributed to hydrophobic humic substances (humic and fulvic acids) which tend to have a greater molecular weight (Fan et al. 2001; Matilainen, Vespalainen & Sillanpaa 2010). The remaining non humic organic content is made up of proteins amino acids and carbohydrates. This fraction of organic content tends to be less hydrophobic (Fan et al. 2001). The non-humic matter is more difficult to remove through coagulation, as it tends to be smaller in size and have a low charge density (Matilainen, Vespalainen & Sillanpaa 2010). The differences in size and properties of all organic matter present in source waters impacts on the treatability of the water by coagulation, the chlorine demand for effective disinfection and the potential for DBP formation.

The larger, hydrophobic, humic substances tend to be naturally varied, and where the pH of the water is greater than 4, they tend to have an overall strong negative charge (MacCarthy 2001; Matilainen, Vespalainen & Sillanpaa 2010). Humic substances tend to have no uniquely, identifiable backbone or skeletal structure. However, there are similarities with how these humic substances act and in general, they tend to contain phenol groups and are rich in aromatic carbon containing conjugated double bonds (Matilainen, Vespalainen & Sillanpaa 2010; Matilainen et al. 2011). A generic structure of a humic substance is shown in Figure 5.

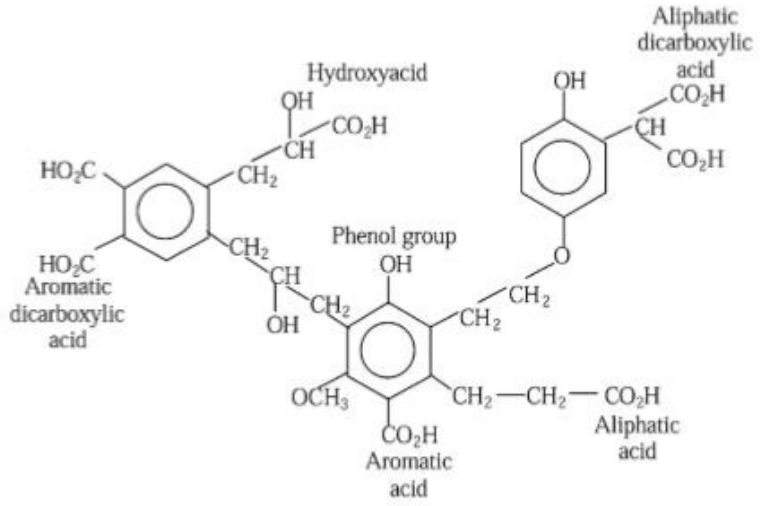


Figure 5: A generic structure of humic acid (taken from Matilainen, Vespalainen & Sillanpaa 2010)

Excitation Emission Matrix (EEM) Fluorescence spectroscopy is widely used to characterise DOC (Chen et al. 2003). The EEM spectrum shows peaks at specific excitation and emission wavelengths where the fluorescence of the molecules is greatest (Matilainen et al. 2011). Using the Fluorescence Regional Integration technique (FRI) developed by Chen et al. (2003), the EEM spectrum gives an indication of the type of molecule that is fluorescing in a specific excitation - emission region (Chen et al. 2003). These regions can be seen in Figure 6.

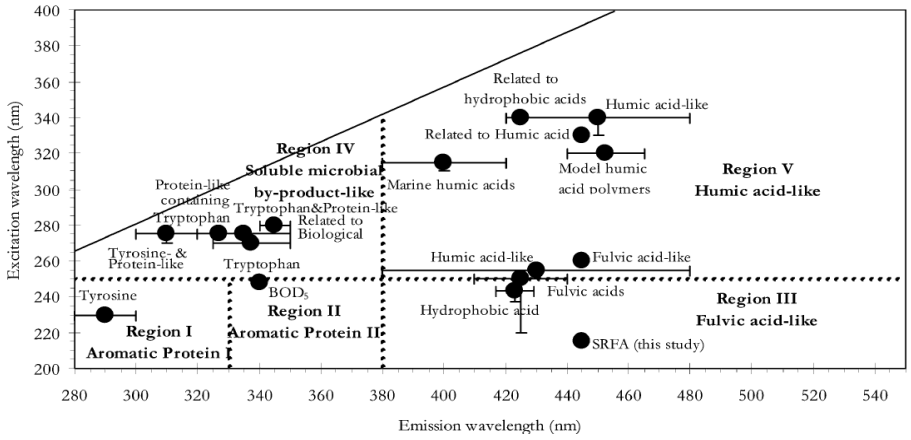


Figure 6: Location of EEM regions based on the excitation and emission wavelengths (Chen et al. 2003)

Further characterisation of the size and composition of the DOC in water can be identified by liquid chromatography – organic carbon detection (LC-OCD). This method uses size exclusion chromatography (SEC) to give a semi quantitative analysis of the distribution of the molecular size of the DOC (Matilainen et al. 2011; Rutlidge et al. 2015). The fractions are distributed into biopolymers, humic substances, building blocks, low molecular weight

(LMW) acids, LMW neutrals and hydrophobic organic carbon (HOC) (Huber et al. 2011; Rutlidge et al. 2015). Further descriptions of these taken from Rutlidge et al. (2015) are shown in Table 2.

Table 2: Descriptions of the fractions obtained from LC-OCD (Rutlidge, et al., 2015)

Fraction	Description
Biopolymers	Organic matter with high molecular weight, e.g., polysaccharides, proteins and amino sugars
Humics	Mixtures of acids containing carboxyl and phenolate groups produced through biodegradation of NOM
Building Blocks	Molecular chains of polyphenolics/poly-aromatic acids that have de-aggregated
LMW Acids	Representing protic organic acids
LMW neutrals	Uncharged small organics including alcohols, aldehydes, ketones, sugars and LMW amino acids
Hydrophobic organic carbon	Fraction of DOC remaining in the column which implies a strong hydrophobic interaction with the column material.

Further quantification of the concentration of the dissolved organic fractions is completed using organic carbon detection. LC-OCDs have been used successfully to characterise the efficiency of water treatment processes in the past (Huber et al. 2011; Matilainen et al. 2011; Rutlidge et al. 2015).

2.3.1 Removal of natural organic matter using coagulation

The most common and effective method of NOM removal is through chemical coagulation where the characteristics of the NOM influence the amount and type of chemical used (Jarvis et al. 2012; Soh, Roddick & van Leeuwen 2008; Drikas 2003). Coagulation and flocculation are two key processes in drinking water treatment which are responsible for the removal of impurities such as turbidity, colour, pathogens, organic and inorganic matter (Twort, Ratnayaka & Brandt 2000; Ghernaout & Ghernaout 2012).

Chemical coagulation is the process where a positively charged coagulant is mixed thoroughly with the raw water forming various complexes (floc), which are dependent upon on the composition of the raw water (Twort, Ratnayaka & Brandt 2000). Flocculation is the process where aggregation of these complexes occurs to aid in removal through a clarification process (Twort, Ratnayaka & Brandt 2000; Ghernaout & Ghernaout 2012). Traditionally chemical coagulation was used as a method for removing larger pathogens, turbidity and colour, with more recent focus being on NOM removal to decrease DBP formation and to reduce chlorine consumption (Soh, Roddick & van Leeuwen 2008). For removal of NOM an inorganic metal coagulant is most commonly used. When added to water the metal salts are dissociated to form a positively charged ion which hydrolyses and forms complexes with both particulate and soluble matter within the water (Matilainen, Vepsalainen & Sillanpaa 2010; Jarvis et al. 2012).

When NOM is present the flocculation processes have been shown as a combination of charge neutralisation, entrapment, adsorption and complexation (Figure 7) (Jarvis, Jefferson & Parsons 2004).

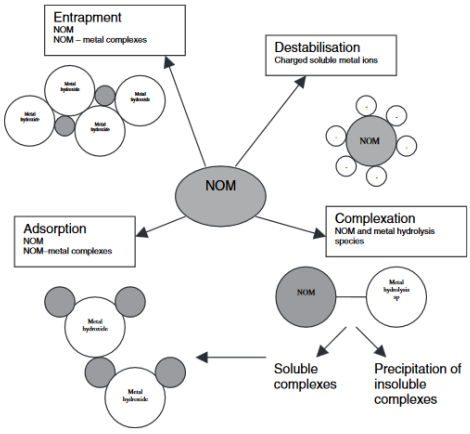


Figure 7: Possible removal mechanisms of NOM during coagulation (from Jarvis, Jefferson & Parsons 2004)

The removal mechanism that occurs is dependent upon the NOM composition including the molecular size, functionality and hydrophobicity (Matilainen, Vepsalainen & Sillanpaa 2010; Jarvis, Jefferson & Parsons 2004). Further to this, even within the same water source the removal mechanism for the different NOM molecules will vary (Jarvis, Jefferson & Parsons 2004). There is evidence to suggest that where NOM is present in high concentrations the floc produced is low density and weak in comparison to flocs produced where turbidity is present (Jarvis et al. 2012; Jarvis, Jefferson & Parsons 2004). This can lead to issues with solid – liquid separation (Jarvis et al. 2012). The effectiveness of coagulation to remove NOM is dependent upon a number of factors including whether the coagulant is pre-hydrolyzed or not. When considering coagulation for NOM removal the pH conditions and the dose rate need to be considered more than for where the key removal parameter is turbidity (Jarvis, Jefferson & Parsons 2004; Soh, Roddick & van Leeuwen 2008; Matilainen, Vepsalainen & Sillanpaa 2010).

The normal method of determining a coagulant dose is using the measures of turbidity and colour as an indicator of effectiveness. However, the conditions for optimal turbidity and colour removal are not necessarily the same as those for NOM removal (Matilainen, Vepsalainen & Sillanpaa 2010). When considering coagulation for NOM removal, the dose and pH conditions need to be considered more than for where the key parameter is turbidity removal (Jarvis, Jefferson & Parsons 2004; Matilainen, Vepsalainen & Sillanpaa 2010).

2.3.2 Interaction of natural organic matter with chlorine disinfection

As previously mentioned where residual NOM is present following the coagulation process, there is potential for DBP formation. In Australia the most commonly formed DBPs are THMs or HAAs (Fabris, Chow & Drikas 2003; Korotta-Gamage & Sathasivan 2017). DBPs form through a reaction between NOM and chlorine that is applied for disinfection purposes, however the mechanisms associated with the formation of DBPs is complex and are dependent upon many factors (Ates, Kitis & Yetis 2007; Roccaro, Vagliasindi & Korshin 2009). To add to the complexity, much research is conflicting, particularly around the formation of HAAs (Bond et al. 2012). In general, the presence of longer chained amino acids increases the HAA formation potential (Bond et al. 2012).

Other than the characteristics associated with the NOM within the water, the type of DBP formed is dependent upon other parameters within the water such as pH, temperature, the presence of bromide and contact time (Twort, Ratnayaka & Brandt 2000; Gallard & von Gunten 2002; Gang, Clevenger & Banerji 2003; Korotta-Gamage & Sathasivan 2017). The influence of pH not only the impacts on the potential for DBP formation but also the type formed. Research has shown that by decreasing the pH prior to disinfection the formation of DBPs is lower, and conversely where the pH is increased the formation of DBPs is higher (Mishra, Gupta & Sinha 2013). Additionally, as the pH increases from pH 7 to pH 11, there is a 30 % to 50 % increase in THM formation in preference to HAAs (Mishra, Gupta & Sinha 2013). In general temperature increases see an increase in the reaction of NOM with free chlorine, increasing the amount of DBPs being formed (Twort, Ratnayaka & Brandt 2000; Mishra, Gupta & Sinha 2013). There is some conflicting research around this, indicating that there is not a linear relationship between temperature and THM formation. Garcia-Villanova et al. (1997) showed there is an optimum point for THM formation at 19°C after which the concentration of THMs decreases (Garcia-Villanova et al. 1997; Mishra, Gupta & Sinha 2013).

The presence of bromide in raw water can impact on the types of DBP formed, especially the ratios of bromide/DOC and bromide/chlorine (Ates, Kitis & Yetis 2007). During disinfection the bromide is oxidised to form hypobromous acid which reacts readily with the residual NOM to form brominated DBPs. As the ratio of chlorine to bromide increases the likelihood of brominated DBPs is favoured (Twort, Ratnayaka & Brandt 2000; Bond et al. 2012; Mishra, Gupta & Sinha 2013).

The final key component that impacts on DBP formation is the chlorine concentration and the contact /reaction time (Garcia-Villanova et al. 1997; Mishra et al. 2013). The general opinion is that THM formation is dependent upon the concentration of the free chlorine. Present and

past research into this area has shown that there is a linear relationship between chlorine demand and the production of THMs (Garcia-Villanova et al. 1997). Research has shown that the bulk of DBPs will form rapidly following the initial chlorine dose, with minimal increase in DBPs being formed after 48 hours (Mishra et al. 2013).

In Australia the concentration of DBPs is regulated on a state basis, however, in general the levels of DBPs permitted in drinking water is higher than Europe or the USA. The regulatory standards seen in these countries have led to a greater emphasis on NOM removal up front (Edzwald & Tobiason 1999; Jarvis et al. 2012). The presence of NOM during the disinfection process increases the consumption of chlorine required to achieve the same pathogen kill rate. This in turn leads to the practice of increased chlorine doses being used, thus increasing the DBP formation potential (Chang et al. 2006).

It is clear that many factors affect taste and odour, and the removal of potentially taste and odour causing materials. The Triple Bottom Line (TBL) analysis is considered as a useful approach to assist in decision making in the selection of suitable treatment. This approach is described in the next Section.

2.4 The use of a triple bottom line assessment in the water industry

TBL assessment is a common tool used by businesses to measure the overall sustainability of a project or as a tool for self-evaluation (Marques, da Crux & Pires 2015). The TBL encompasses financial, social and environmental aspects of the project or process being assessed (Slaper & Hall 2011). In the water sector the use of financial performance as a measure of commercial viability was used during the 'economic reform era' of the 1980s and 1990s. The changes in regulation of the economy resulted in changes to the governance around the urban water sector (Infrastructure Partnerships Australia 2015). Since this period the overall sustainability of the sector was reviewed and the use of a multi-criteria assessment became common (Marlow, Beale & Burn 2010; Adams, Muir & Hoque 2014). Despite the industry's efforts to assess the sustainability of a project through the assessment of social, environmental and financial impacts, it has been found that there is often a shortfall. This is mainly due to the stakeholders involved and their conflicting priorities (Lundie et al. 2006; Marques, da Crux & Pires 2015). In both South Australia (SA) and Western Australia (WA), the basic concepts of the TBL have been shifted slightly to take into consideration time dimensions as well as political and technological dimensions (Lundie et al. 2006). As the services provided by the water industry underpin societal needs, the industry is in a position to be a leader in sustainability and requires a holistic view (Lundie et al. 2006; Lai, Lundie & Ashbolt 2008; Marques, da Crux & Pires 2015).

3 Methodology

This chapter details the approach taken for this research. The chapter consists of 3 Sections, Section 3.1 describes how the taste and odour issues were identified. Section 3.2 contains information regarding the optimisation of the treatment process for taste and odour removal. Section 3.3 discusses the method taken to complete the TBL assessment.

3.1 Identification of the taste and odour issues

This section details the process for the identification of the causes of taste and odours at Euroa WTP. This was completed through the use of a taste and odour panel to identify the key taste and odours in the water. The identified taste and odours were then correlated to water quality data from the same period to understand any pertinent relationships.

3.1.1 Water quality data analysis

Raw and final water quality data from 2004 to 2014 was obtained from the GVW Water Quality database "Aquantify" and analysed. Data analysed was for the following parts of the process:

- Raw water;
- WTP process data including post clarification and filtered waters;
- Treated water prior to entry to town following disinfection; and,
- The reticulated water.

Two sources of data were analysed, externally analysed data and field data. The external laboratory data was obtained from SGS Laboratories, a NATA accredited laboratory which uses *Standard Methods for the Examination of Water and Wastewater*. All field data analysed was collected using GVW standard bench top testing equipment as per the manufacturer's guidelines.

External laboratory data included UV transmittance (UVT), DOC, TOC, THMs, HAAs and iron and manganese contents. Field data comprised free and total chlorine, electrical conductivity, turbidity, pH and true colour. Meta-analysis, that is an analysis of various archived data sets from GVW, was undertaken to understand seasonal variations and correlations to other water quality parameters.

Where existing data were not available, or the data were limited, a weekly program for further sampling and testing was undertaken over the summer period of 2014/15. Characterisation was done by SGS or in the field. Water was characterised at the raw water sources (Abbinga Reservoir, Waterhouse Reservoir, Mountain Hut Reservoir /raw water inlet) as well as post clarification, post filtration, and pre - and post - CWS following disinfection.

3.1.2 Taste and Odour Identification

Ethics approval was given by the College Human Ethics Advisory Network (CHEAN) of the Science Engineering and Health (SEH) College, RMIT University to enable the use of GVW staff for the taste and odour panels. Initial approval was given on the 27th September 2013 to undertake large scale engagement in order to understand community perceptions of taste and odour. This was amended and approved on 9th December 2014 to include the use of only GVW staff. The ethics approval number was BSEHAPP 38-13 and approval letters are included in Appendix 1.

Taste and odour testing was undertaken using a panel of volunteer GVW staff. Where water had been treated to GVW standards in accordance with the Victorian Safe Drinking Water Act (SDWA (2003)) and the Victorian SDWR (2015), the panel members were asked to undertake taste and odour testing on the water samples. Where the water was considered to be partially treated or did not conform to GVW standards, only odour testing was undertaken for safety reasons.

An email was sent to GVW staff based at the Regional Administration Centre (RAC) in Shepparton asking for volunteers to undertake taste and odour testing with 30 staff responding positively. All volunteers were read a standard piece of text (Figure 8) informing them that by being involved they consented to the data collected to be used for the purposes of this study, no personal information would be used and they were free to opt out of the study at any point.

"You have a number of samples in front of you and a worksheet to fill in your perceptions. There is no right or wrong answer, only your personal views and perceptions. All the water is safe to drink and you are able to taste and smell the water as many times as you like.

Taste and smell your samples in order. Start by smelling the water. To do this swirl the sample holding the watch glass on top of it, lift the watch glass and inhale deeply. Using the guide words on the bottom of your worksheet, write down your perceptions of what you believe the water smells like, then allocate a strength rating to it, where 1 means you can barely smell it and 5 is very strong.

Next take a mouthful of the sample and swirl it around your mouth; drawing air through your teeth. Using the guide words on the page write down what your perceived taste is. As with the smell, write down the perceived strength.

Lastly write down your overall view of the water, where 1 is undrinkable and 5 is extremely good.

Repeat this process with the remaining samples. Once this has been done you are free to go. Please ensure your name is written on the top of your sheet, any personal data will be coded and your responses will be anonymous in any subsequent analysis. Feel free to ask any questions throughout the process."

Figure 8: Standard text which was read to taste and odour panel

On a weekly basis not all volunteers were available to be involved in the panel due to prior commitments. This meant that the panel composition changed on a weekly basis depending on the availability of the participating GVW staff. On average each panel contained 13 participants. Of these 13, at least 6 of the members were the same each week.

One - litre samples of potable water were collected from GVW sampling locations supplied by the Euroa WTP and a fourth sample was taken from the Regional Administration Centre (RAC) in Shepparton as a control location (Table 3). The decision to use the Shepparton RAC as a control was made as the panel were all based in this location and drink the water daily. Therefore, it was assumed that the perceptions of this water should be consistent against the unknown samples from Euroa. The samples were tested on the same day of collection at room temperature (between 18 and 23°C).

Table 3: Sampling locations used for taste and odour testing

Sample	Sample Location
1	Euroa CWS
2	Euroa Reticulation System
3	Violet Town Reticulation System
4	Shepparton RAC

Approximately 30 mL of each sample was transferred into a tasting glass and covered with a watch glass. Each sample was labelled with a non-identifiable tag to remove any pre-conceived bias about the taste and odour of the sample location. These non-identifiable tags changed weekly to remove any pre-conceptions.

Using the instructions given in Figure 8 the panel were asked to smell the samples firstly, followed by tasting them. Samples that did not conform to water safety standards were removed before taste testing but after all odour testing was complete to minimise bias. All results were recorded on the pro-forma (Figure 9).

Each week the order of the samples was changed to remove any potential bias associated with a particular sample. All data collected were recorded removing any personal identification.

NAME DATE

Sample	Odour Analysis		Taste Analysis		RATING
	Description	Strength	Description	Strength	
A					
B					
C					
D					

ODOUR Descriptors				
NONE	Chlorinous	Earthy / Musty	Chemical	Other
TASTE Descriptors				
NONE	Sweet	Sour	Salty	Bitter
STRENGTH (The strength of a taste and odour is judged according to the following scale)				
1 - threshold	2 - weak	3 - moderate	4 - strong	5 - disgusting
RATING (The overall rating for the taste and odour of the water)				
1 - undrinkable	2 - poor	3 - good	4 - very good	5 - excellent

Figure 9: Taste and odour panel worksheet

It was suspected that there were certain locations where particular tastes and odours were strong and from this the null hypothesis was developed that the taste and odour of the sample and the sample location were independent. The significance level used was $p < 0.05$.

The data analysed were collated and counted for each taste and odour detected against the location. From this the expected number of taste and odour detections against each location was determined using Equation 1. From this the Chi Squared value (X^2) was able to be determined using Equation 2

$$\boldsymbol{Expected\ Value = \frac{Row\ Total\ x\ Column\ Total}{Total\ Observations\ in\ the\ table}} \qquad \textbf{Equation 1}$$

$$\boldsymbol{X^2 = \sum \frac{(observed - expected)^2}{expected}} \qquad \textbf{Equation 2}$$

Where specific odours were identified by the panel, Suffet et al. (1999) was used to cross reference the identified odour with known odour causing chemicals. Once identified, these compounds were analysed with respect to their odour detection thresholds (ODT).

The water quality parameters mentioned in Section 3.1.1 were used to understand the relationship to odour. The count of each odour detected was collated by month and compared to the average water quality data of the same month. The seasonality of the water quality parameters was consistent and therefore this approach was considered to be representative. Where the relationships appeared to be linear, these were correlated using Pearson's correlation coefficient with a significance value of $p < 0.05$.

3.2 Optimisation of the treatment processes for taste and odour removal

Following the identification of the key taste and odour compounds, jar testing was completed to understand the impact on odour removal. The existing chemical coagulant dosing was reviewed and optimised for odour improvement. The optimisation targeted the water quality parameters which were identified as relating to odours as determined in Section 3.1.2. Alternative chemical coagulants were trialled with respect to odour improvement.

3.2.1 Jar testing for taste and odour removal

Jar testing was completed using aluminium sulphate, aluminium chlorohydrate (ACH) and ferric sulphate as coagulants. The method followed is detailed by Murray and Mosse (2015).

Coagulant stock solutions were made up at the beginning of each month based on the guidance provided by Murray and Mosse (2015). Caustic soda stock solution was made using 3.65 mL of 46% caustic soda and made up to 250 mL with deionised water. Aluminium sulphate stock solution was made using 16.25 mL of 47% aluminium sulphate and made up to 1000 mL with deionised water. Ferric sulphate stock solution was made using 13.48 mL of 12 % ferric sulphate and made up to 1000 mL with deionised water. ACH stock solution was made using 14.93 mL of 40% ACH and made up to 1000 mL with deionised water.

A four - jar Platypus jar testing system with 2 L beakers was used. It was set to operate at 120 rpm for 2 minutes to replicate flash mixing conditions at Euroa WTP, and 30 rpm for 20 minutes to replicate flocculation time and allow floc to form.

The jars were left for 20 minutes following flocculation to allow the floc formed to settle. After settlement water was drawn from the top of the jar 5 cm below the surface, and the pH, turbidity, true colour and UVA were determined using GVW standard instruments using manufacturer's instructions. These data were used to identify the most effective dose as indicated by the lowest turbidity, colour and UVA.

Turbidity was determined by a HACH 2100 N turbidimeter in a 30 mm glass sample cell. pH was determined in situ using a Eutech waterproof pH meter. Determination of true colour and UVA required samples to be filtered through a 0.45 µm syringe filter. True colour was determined using a HACH DR 2700 Spectrophotometer at 540 nm in a quartz cuvette with 50 mm path length. UVA was determined using a Realtech portable UV field meter at 254 nm in a quartz cuvette with a path length of 10 mm. The Realtech Portable UV field meter has the ability to give outputs of both UVT and UVA. UVT has a logarithmic relationship to UVA and can be converted using Equation 3. Deionised water was used as a blank for UVA and true colour.

$$UVA = 2 - \log_{10}(UVT) \qquad \textbf{Equation 3}$$

Further analysis of the most effective doses was completed by SGS Laboratories where DOC and UVT were determined. These were then compared to the WTP performance post clarification.

A 1 L graduated Imhoff cone was used to determine the volume of wet sludge in cm^3/L. After all the required supernatant samples had been removed after settling, the remaining one litre was transferred to the Imhoff cone and allowed to settle for 20 minutes. The volume of wet sludge was determined after this time using the graduations on the cone.

After completion of the jar tests, the odour of the most effective coagulant dose was determined using the taste and odour testing panel from Section 3.1.2 and compared against the odour from the WTP and the raw water. Data were analysed using the Chi squared statistic (Section 3.1.2). As the water was not considered to be potable following the jar tests the panel were asked to assess only the odour.

3.2.2 Fluorescence excitation-emission matrix spectra

Selected samples underwent further organic analysis using EEMs. This was to understand the changes in the composition of organic matter following treatment.

All samples were filtered through a 0.45 µm filter and the fluorescence EEM spectra were determined using a LS55 PerkinElmer Spectrometer over excitation and emission wavelength ranges of 220–465 nm and 280–550 nm, respectively. The band width for both excitation and emission was set at 5 nm. Data was analysed using the Fluorescence Regional Integration (FRI) technique detailed in Chen et al. (2003).

Although the method outlined by Chen et al. (2003) has been superseded by more accurate techniques for interpreting EEM spectra, the FRI was considered to be sufficient for the purposes of this study as it gave an indication of the volumes for each of the regions and thus presence of the different fluorescent compounds.

3.2.3 Liquid Chromatography – Organic Carbon Detection

Following the jar test completed on the 28/4/2017, 50 mL of each sample was sent to the Water Research Centre at the University of New South Wales. The molecular weight distribution of the organic compounds in each sample was determined using a DOC-Labor LC-OCD Model 8, with a Toyopearl TSK HW -50S Column. A phosphate buffer of pH 6.4 was used as the mobile phase.

3.2.4 Replication of post-coagulation chemical dosing in the jar tested samples

A 1 L sample of supernatant from the most effective coagulant dose from the jar tested samples was filtered through a Whatman #1 filter and 20 µL of 12.5% sodium hypochlorite solution was added to achieve an equivalent dose rate of 3 mg/L as dosed at Euroa WTP.

Where the pH of the jar tested samples was below pH 6, caustic soda was added to the 1 L sample using an Eppendorf multipette M4 in 1 µL increments until the pH reached 6.2. This was completed prior to chlorine addition to mimic the disinfection process at Euroa.

The free chlorine residual was determined using the addition of a HACH free chlorine DPD powder pillow to 10 mL of sample and analysed using the HACH Pocket Colorimeter II within one minute of addition.

After a minimum of 6 hours, a sample was collected and sent to SGS Laboratories to determine DOC, THMs and HAAs.

3.2.5 Improvement of settling of the ACH Floc

The floc produced through ACH coagulation was considered likely to be inadequate for use in the clarifier at Euroa and it was necessary to increase its density to enable satisfactory settlement. Polymer addition was trialled and the sludge volumes determined. Flopam 4190 PWG was trialled as this is the polymer used at Euroa WTP. The polymer strength used was 0.25% w/w.

Using a similar method described in Section 3.2.1, the same ACH dose was applied for each jar test on the raw water quality. Polymer was added in 0.1 mg/L increments between 0.1 mg/L and 0.4 mg/L.

The volume of wet sludge produced was determined using a 1 L graduated Imhoff cone.

The addition of a 10% suspension of bentonite was trialled to increase the particulates prior to coagulation to improve settling. The bentonite used was AccoFloc 200, sourced from Amcol. As with polymer addition, the same ACH dose was added to each jar based on the raw water quality. The bentonite solution was added in 2 mL/L increments up to 8 mL/L. The jar test then proceeded as per the method prescribed in Murray and Mosse (2015).

3.3 Triple bottom line analysis

The GVW TBL assessment tool was used to compare the alternative coagulation chemicals and the optimisation of aluminium sulphate as the current coagulant in the current plant operation. Limitations on the assessment boundary were drawn at the point where GVW had no direct influence on the output.

Economic, social and environmental assessments were conducted. A workshop was organised using three key GVW staff members and for each item assessed a rating was given based on the descriptors in Table 4. The rating was achieved through discussion and consensus.

The total score was then aggregated for each assessment, weighted and ranked. Table 5 details the weightings used as part of the triple bottom line assessment.

Table 4: Descriptors used as part of the triple bottom line assessment

Rating	Description
-4	Major Negative Impact
-3	Moderate Negative Impact
-2	Minor Negative Impact
-1	Minimal Negative Impact
0	No Impact
1	Minimal Positive Impact
2	Minor Positive Impact
3	Moderate Positive Impact
4	Major Positive Impact

Table 5: Weightings used in the triple bottom line assessment

	Economic Assessment	Environmental Assessment	Social Assessment
Weighting (%)	35	30	35

A sensitivity analysis was used to test the outcomes of the initial TBL assessment by increasing the weightings to favour the economic, environmental or social aspects. The weightings used in the sensitivity analysis are shown in Table 6.

Table 6: Weightings used to undertake a sensitivity analysis to test the outcomes of the TBL assessment

	Economic Assessment	Environmental Assessment	Social Assessment
Sensitivity Analysis 1 (%)	50	25	25
Sensitivity Analysis 2 (%)	25	50	25
Sensitivity Analysis 3 (%)	25	25	50

3.3.1 Economic assessment

The economic impact was assessed with respect to the operational costs and the potential impacts on the GVW infrastructure program. The operational costs consisted of the overall impact on chemical costs and the cost to removal sludge to landfill.

3.3.1.1 Operational cost impacts

GVW process data were collected from the GVW supervisory, control and data acquisition (SCADA) system and GVW's water quality database for the 2014 period. The data resolution used was hourly readings over a 12 - month period and therefore considered as representative of the Euroa WTP site operation.

Aluminium sulphate, pre caustic soda, post caustic soda and flow set points were collected from SCADA, and the disinfection system set points were collected from the water quality database for the 12-month period. These were used to determine the chemical cost per ML of water produced by the WTP.

Chemical costs associated with water production were determined using GVW chemical contract prices. The raw chemical costs are given in Table 7.

Table 7: Raw chemical costs taken from the GVW chemical contract

Chemical	Cost
Aluminium sulphate	$220 / t
Aluminium chlorohydrate	$1007.38 / t
Ferric sulphate	$385 / t
Polymer (Flopam 4190 PWG) (0.25% w/w)	$170/25kg bag = $6.85 / kg
Caustic soda	$478.58 / t
Chlorine	$7.21 / kg

The most effective jar test doses were used to determine the chemical costs per ML of water produced if implemented.

The chemical dose rates determined from the jar tests completed following the method outlined in Section 3.2.1 were converted from mg/L to kg/ ML. The prices of the chemicals shown in Table 7 were then used to determine the cost per ML ($ /ML) of water produced.

The volume of sludge produced (Section 3.2.1) was used to understand the cost of removal to landfill. An average volume of 710 ML of water produced per year was used and a cost of $175 / t of wet sludge removed was used to determine the annual cost.

3.3.1.2 Impact on Goulburn Valley Water's infrastructure program

For each chemical assessed through jar testing (refer to 3.2.1) the volumes of chemicals which would be required on site were determined and the existing chemical storage was assessed for viability. Similarly, the volumes of sludge to be produced were determined and the impact on

the existing sludge handling facility was assessed for suitability. From this an assessment was made whether the existing infrastructure would require modification.

3.3.2 Environmental assessment

The environmental assessment consisted of analysing each coagulant for potential greenhouse gas (GHG) emissions based on the volume of chemical to be delivered to site per year. Data from Seo, et al., (2016) detailing the carbon dioxide (CO_2) emissions per km driven was used to determine the maximum volume of CO_2 emitted for each chemical. This method was also used based on the volume of sludge to be removed to landfill and the associated GHG emissions.

Similarly for each coagulant the volume of sludge produced based on an annual treated water production of 710 ML was determined and the potential impacts on disposal to landfill were considered, including where beneficial reuse was applicable.

3.3.3 Social assessment

The social assessment took into account the impact that changes in taste and odour would have on both the community and GVW employees, with particular consideration given to the impact on the site operator.

Items considered when determining the impact on the site operator were exposure to chemical hazards and the ease of site operation. The site operation considered jar testing requirements, the operability of the clarifier and sludge management. For GVW employees change in the level of work satisfaction was considered based on previous research looking into the correlation between improved service levels to the community and staff pride using previous work undertaken by Bulgarella 2005.

Community aspects were determined using previous research into taste and odour impacts on the community including work by Jardine, Gibson & Hrudey (1999) and Sinclair, Leder & Chapman (2005).

4 Taste and odour perceptions

This chapter explores the underlying taste and odour issues and examines the potential causes of the issue. A review of water quality parameters was completed with respect to the odours detected to provide the operator of some warning where a potential taste and odour issue may occur.

4.1 Identification of taste and odour issues based on historical and background data analysis

Euroa and Violet Town have long had an underlying taste and odour issue with residents informally notifying staff that the water tasted and smelled bad, conversely, there are very few formal complaints (Average 5 per year since 2001) which is in line with the findings in Chapter 2, which suggest that for every complaint made there are approx. 20 others who do not. In order to understand the issues seen in the township, the existing tastes and odours were identified.

4.1.1 Determination of key taste and odours

Perceptions of taste and odour against the location of the water sample were tested for independence. When looking at the odours, three categories (earthy /musty, chemical /chlorine and none) from four different locations were tested for independence using the Chi squared test ($X^2 = 27.79$, $p = 1.03 \times 10^{-4}$). Against a p value of 0.05 the result is considered to be significant, therefore the null hypothesis (H_o = the odour detections and the water sampling locality are independent) was rejected. This indicates that the panel were able to distinguish different odours from the different sample locations. Table 8 shows the observed odour detections and the calculated expected values (in brackets) from the Chi squared test for independence.

Table 8: Observed and expected odour counts determined by the taste and odour panel

	Chlorine /chemical	Earthy /musty	None
CWS outlet	60 (42)	28 (26)	23 (44)
Euroa reticulation	36 (44)	28 (27)	53 (46)
Violet Town reticulation	26 (34)	21 (21)	45 (36)
Shepparton RAC	12 (14)	6 (9)	20 (15)

The panel clearly indicated that the odour of the samples from the outlet of the CWS at the entry point to town was chlorine/chemical. Although the chlorine odours were still present in the sample when taken from the reticulation system in Euroa, these were less than the expected

values. Similar findings were found in the Violet Town samples. The panel determined that earthy/musty odours were present in the CWS sample and also in the samples taken from the reticulation systems in Euroa and Violet Town. All of these results are in line with the expected values and it can be concluded that earthy /musty odours will often be present in Euroa water. In the reticulation systems of both Euroa and Violet Town there were more 'no odour' detects that the expected values, whereas the outlet of the CWS had fewer 'no odour' detects than expected.

Based on the comparison of the observed and expected results it is apparent that the odours being detected are changing as they move through the reticulation system. This is likely due to interactions of chlorine and any dissolved matter (both organic and inorganic) in the water. There is also potential that interactions with biofilms within the distribution pipe network could cause a change in odours.

A similar process was used for taste detections. The Chi squared test for independence was determined against the location ($X^2 = 10.07$, $p = 0.61$), using a p value of 0.05, the null hypothesis (H_o = the taste and sample locality are independent of each other) was accepted. This means that the panel was unable to determine any difference in taste between locations. The observed and expected results (in brackets) are shown in Table 9

Table 9: Observed and expected values from taste testing panels

	Bitter	**None**	**Salty**	**Sour**	**Sweet**
CWS outlet	30 (26)	15 (16)	20 (23)	23 (23)	13 (12)
Euroa reticulation	27 (31)	22 (18)	25 (26)	26 (27)	17 (14)
Violet Town reticulation	20 (24)	11 (15)	26 (21)	26 (21)	9 (11)
Shepparton RAC	14 (10)	7 (6)	7 (8)	6 (9)	4 (5)

The data from Table 9 indicates that the panel were unable to distinguish between the tastes of the water from different locations. However, the data in Table 8 shows that the panel were able to discriminate odours from different locations. In general a person's perceptions of overall flavour is a combination of the odour and the taste of the water (Burlingame, Doty & Dietrich 2017), it is likely that the panel's perceptions are influenced mainly by the odour which showed a greater sensitivity to location. Thus, it can be considered that the panel are more accurately able to determine the odours from a particular location.

4.2 The Relationship of water quality parameters with respect to identified odours

From Section 4.1, the panel determined the key odours at Euroa are earthy /musty and chlorinous. From the literature, it is known that geosmin and MIB are key contributors to earthy /musty odours within the source waters and chlorine has the ability to mask or oxidise these odours (Suffet, Mallevialle and Kawczynski 1995, Wnorowski 1992). Both geosmin and MIB have been detected in the Euroa raw water in the past, however there was limited data to show if the ongoing odours were related to these detections.

Geosmin and MIB levels were analysed in the raw water and the final water at Euroa between December 2014 and June 2016 to understand their impact on odour from the WTP (Figure 10).

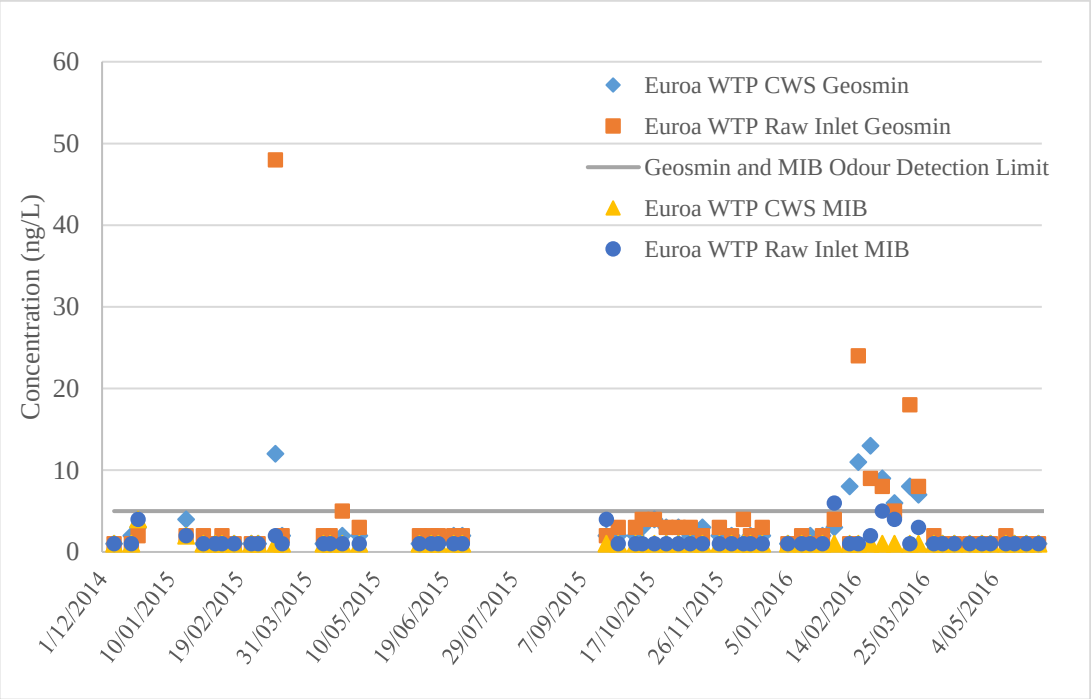


Figure 10: Geosmin and MIB detections from the raw and final waters at Euroa WTP between December 2014 and June 2016

Figure 10 shows that between December 2014 and June 2016 there were seven geosmin detections and one MIB detection in the raw water at Euroa WTP above the lowest ODT limits of 5 ng/L. Similarly there were seven geosmin detections in the period which were above the ODT at the outlet of the Euroa WTP prior to entry into the distribution network, however no MIB results were above the odour threshold limit for the same period. For the period between January 2016 and March 2016, where geosmin was present above the ODT, there were no corresponding taste and odour complaints to GVW for this period. These results indicate that although geosmin and MIB were present, they cannot be considered as the key contributors to ongoing earthy /musty taste and odour issues at Euroa.

The other key odour that was detected by the panel was chlorine odours, particularly at the outlet of the CWS prior to entry to the reticulation system. Figure 11 shows the pre and post CWS free chlorine residual over the time period between December 2009 and October 2016.

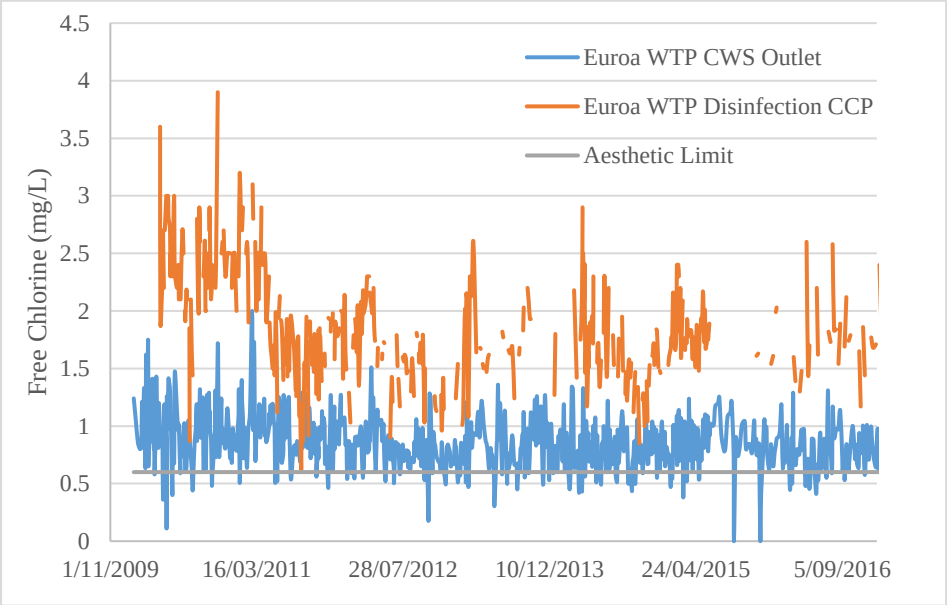


Figure 11: Free chlorine residual between December 2009 and October 2016 taken from the disinfection point pre-CWS and the sample point at the outlet of the CWS.

The ODT for chlorine in water can be as low as 0.2 mg/L depending on the sensitivity of the person (NHMRC, 2011). However the aesthetic limit given in the ADWG is 0.6 mg/L (NHMRC, 2011). The chlorine concentration at the outlet of the CWS at Euroa was on average 0.86 mg/L, which is above the ODT. The operators at Euroa WTP explained that due to the organics in the water, a high chlorine dose was required to ensure a free chlorine residual in the reticulation system. Figure 12 shows that the free chlorine residual at the end points of the Euroa system have been as low as 0.04 mg/L and tend to be lower further from the WTP. The data shown in Figure 12 was taken from the GVW compliance sampling program. Free chlorine determinations were done weekly in the reticulation system between February 2012 and February 2017. The free chlorine ranges were averaged and determined across this period at each sample point (n = 53).

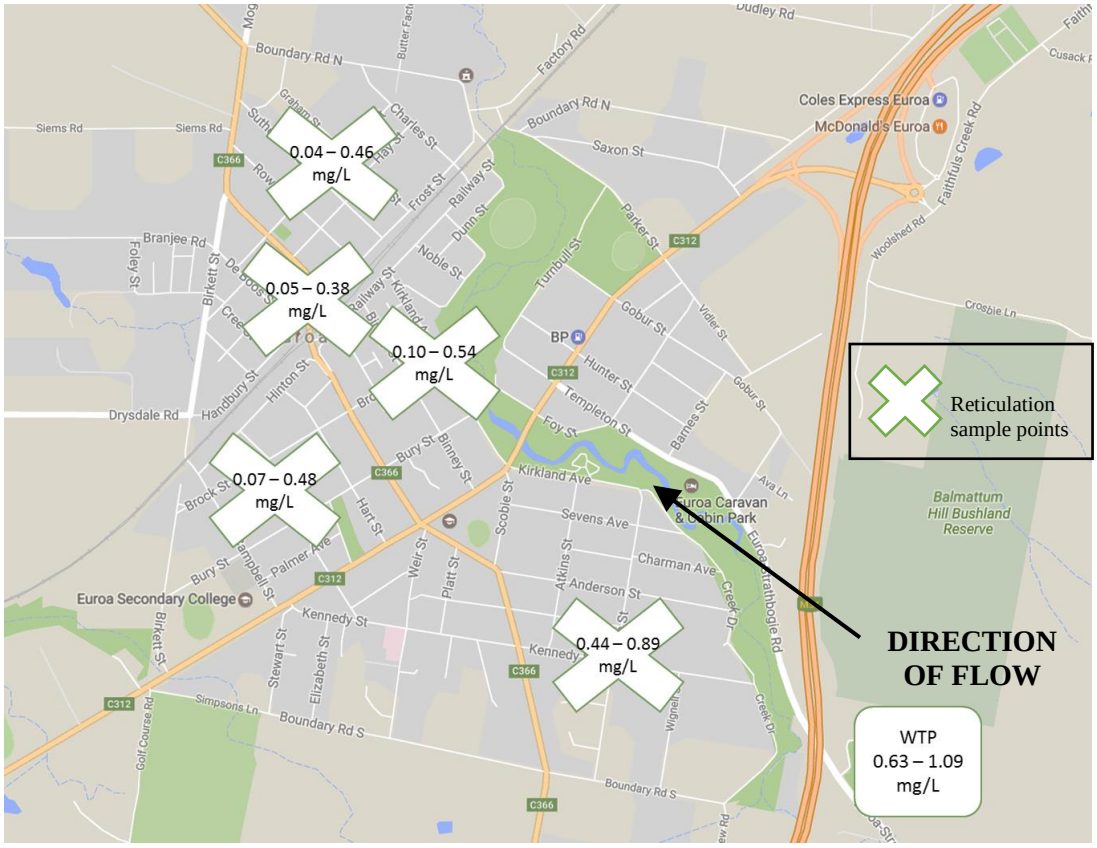


Figure 12: Ranges of free chlorine residual at reticulation points in Euroa based on five years data taken from the GVW compliance monitoring program

The lower than expected observed chlorine odours value in Table 8 can be attributed to the obvious decline in free chlorine residual as the sampling points move further from the WTP. The finding that observed odours in the reticulation system appear to change from chlorine odours to no odours or earthy /musty odours is in line with literature indicating that as the free chlorine in the system dissipates, there will be a recurrence of an earthy /musty odour (McDonald et al. 2013; Puget et al. 2010). The increased no odour detections by the panel in the reticulation system could be due to the reaction of chlorine with any oxidisable odorous compounds present. This is in combination with the decrease of free chlorine present would likely reduce the levels of odours seen by the panel. This is in line with literature which suggests that chlorine can be used as a method of controlling tastes and odours. Where the system uses chlorine to mask earthy /musty odours, it was likely to get a re-emergence of these odours as the chlorine dissipates through the system, however when the chlorine was fully controlled for taste and odour, there was minimal to no odour issue in the samples (Water Research Foundation 2014). In the case of Euroa WTP, the chlorine is dosed specifically for disinfection and to achieve a suitable contact time between the chlorine and the water (C.t) for pathogen removal. The understanding by the operator that the chlorine demand increases with organic matter present would indicate that the operator would have some measure of

understanding around the organic matter, but it is unlikely that they would consider this as a method to improve the taste and odour. However, if the odours in the reticulation system are caused by the organic matter in the water then it is logical to assume that the operator would have some measure of control of taste and odour by utilising chlorine.

4.3 The use of water quality parameters to identify where odours may occur

Based on the odours identified in 4.1.1, odour detections in the reticulation system were correlated to standard water quality parameters used by the WTP operators at GVW.

A number of significant results were identified and results of note were further analysed and detailed in this section. Where a relationship was not considered to be significant or noteworthy, it was not explored any further.

4.3.1 Raw water quality parameters

In relation to raw water quality the only parameter that correlated to the odours in the final reticulated water was SUVA.

As noted in Chapter 2, Table 1, where SUVA values increase, the nature of the organic matter changes, increasing in aromaticity and in general, molecular weight. When using chemical coagulation, increasing SUVA indicates that the nature of the organic matter within the raw water means that it is more likely to be removed through coagulation. In the case of Euroa WTP where there is high SUVA in the raw water, there is a decreasing DOC concentration seen in the clarified water. This would result in a lower concentration of NOM in the final water. In turn, this should result in a lower chlorine demand, improving the ability of the WTP operator to maintain a stable chlorine residual throughout the reticulation system. Therefore, it is assumed that increasing SUVA would result in a lower number of chlorine odour detections. This is confirmed in Figure 13 which shows the relationships between odour detections and SUVA.

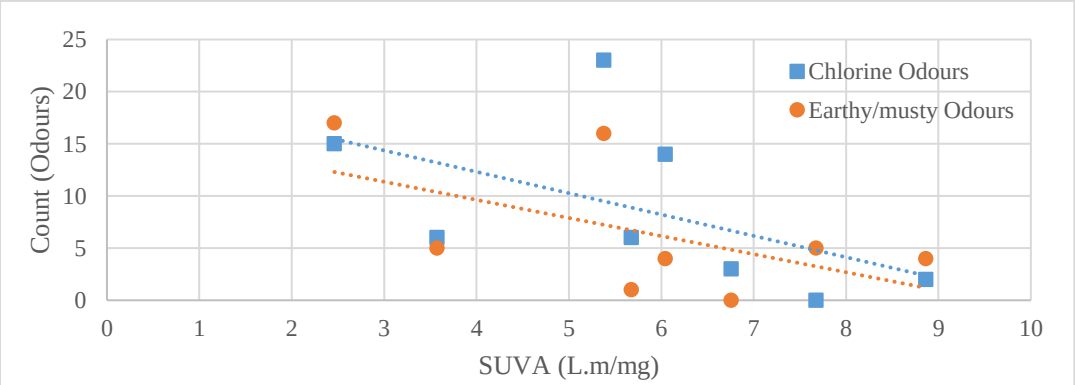


Figure 13: The count of earthy /musty and chlorine odours detected correlated to related SUVA values

Figure 13 shows there is a decrease in the number of samples which have a chlorine or earthy /musty odour detected as SUVA increases. This is confirmed by the Pearson's correlation coefficient for chlorine odours detected which is significant ($r(18) = -0.69$, $p = 0.02$). The relationship between the number of earthy /musty odours detected was considered to also be significant using Pearson's correlation coefficient where $p < 0.05$ ($r(18) = -0.66$, $p = 0.03$).

This suggests that GVW could potentially use SUVA as an indicator of where chlorinous and earthy /musty odours may occur in the final water at Euroa. This would allow the WTP operator to focus on both the free chlorine residuals and the optimisation of the coagulant chemical dosage to reduce the likelihood of odours in the final water. In general, at the Euroa WTP, where there was a higher SUVA value determined, the post clarification DOC was lower which, may also explain the lower number of odours detected.

As mentioned previously SUVA is determined using UVA and DOC. At present there is no easy way for the WTP operator at Euroa to test for DOC, nor is there an online analyser installed. However, UVA is a simple parameter to measure using a bench top instrument which would allow the operator to understand where a potential taste and odour issue may occur. Therefore, use of DOC and UVA in relation to potential odour detection was explored further.

Figure 14 shows the relationship between UVA and the odours detected by the panel.

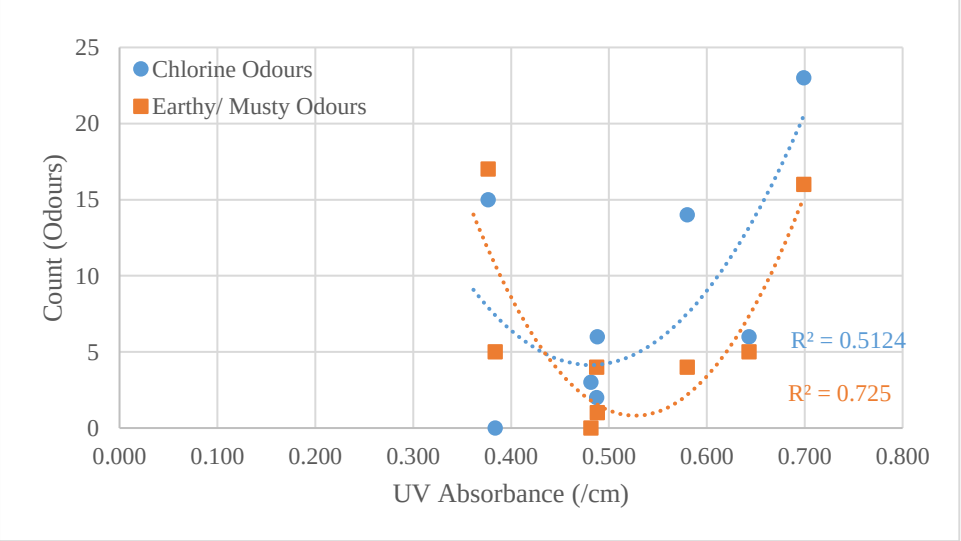


Figure 14: The count of chlorine and earthy /musty odours detected in comparison to the UV absorbance and odour detections

The data shown in Figure 14 demonstrates that there is not a strong relationship between UVA and the chlorine odours detected, whereas the relationship with earthy /musty odours appears to be moderate to strong. For both odours there appears to be a point at UVA = 0.48 /cm where there are minimal odours detected.

Although UVA is used to determine SUVA, the raw water SUVA values at Euroa appear to be less influenced by the UVA than expected. This is shown in Figure 15.

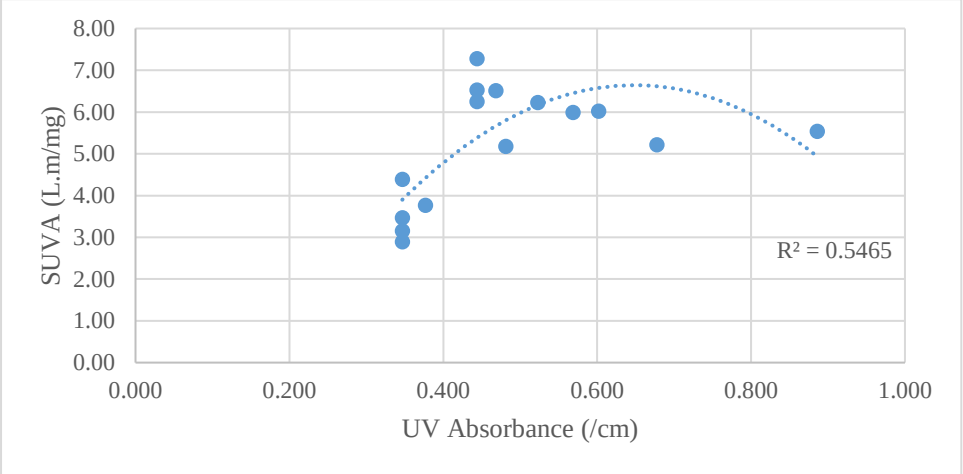


Figure 15: SUVA with respect to UV absorbance

The data shown in Figure 15 is consistent with the relationships shown in Figure 14 demonstrating that at around UVA = 0.48 /cm there are minimal odours detected from the samples taken at Euroa WTP. The UVA at this point coincides with a higher SUVA which supports the findings of increasing SUVA decreases the number of odours detected. In general, at the Euroa WTP, when a higher SUVA value was determined, the post clarification DOC was lower which may also explain the lower number of odours detected.

Similarly, when looking at the raw water DOC with respect to the odours detected, given the potential for NOM to cause odours, it was anticipated that there would be a strong relationship. The results were explored and are shown in Figure 16.

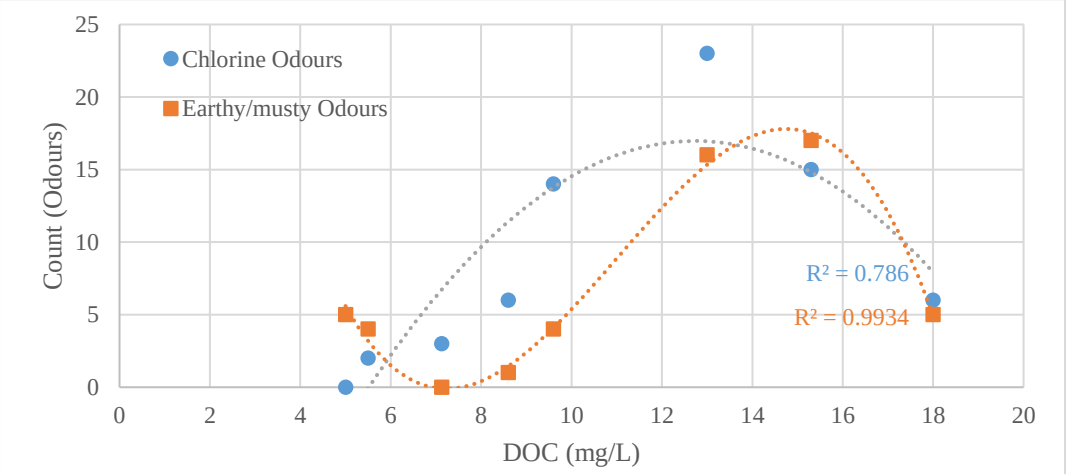


Figure 16: The count of chlorine and earthy /musty odours detected with respect to DOC.

The relationship between the odours detected and DOC again are not linear however there is a general trend that with increasing DOC there is increasing odours detected. Both relationships show complex interactions with the number of odours being detected peaking at around 12 mg/L DOC. However, in general there is a trend of increasing odour detections with increasing DOC.

In line with the literature where NOM has been known to cause odours (Drikas 2003), there appears to be a stronger relationship between the earthy /musty odours and DOC. Because the detection of chlorine odours decreases after 12 mg/L DOC it is likely the DOC remaining in the water post clarification is lower which in turn has a lower chlorine demand requiring a lower dose rate.

This decrease in odours detected at higher levels of DOC is likely due to a change in composition of the raw water organics to be potentially more favourable to removal of odorous organic compounds through the treatment process at Euroa WTP. There is also potential for climate conditions such as water temperature, rainfall volumes and the season to have influenced the characteristics of NOM present. Unfortunately, the current data set was not collected in a sufficiently consistent manner to draw any conclusions as to the effect. As SUVA gives a good indication of potential removal affinity of organic matter through coagulation, the DOC concentration with respect to SUVA was reviewed. These results are shown in Figure 17.

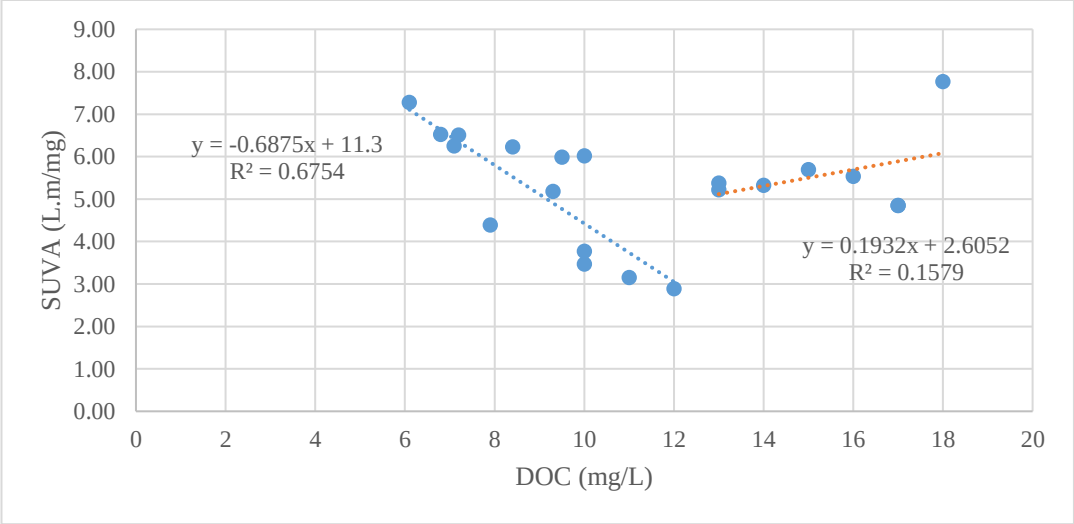


Figure 17: SUVA with respect to DOC

Figure 17 shows that where the DOC increased above 12 mg/L (the right hand side of Figure 17), the SUVA value remained constant at around 5 L.m/mg. Although it is uncommon that the DOC concentration is seen at this level, this confirms the reasoning proposed around the reduction in the detection of chlorine and earthy /musty odours with increasing DOC.

Therefore, up to DOC = 12 mg/L (the left hand side of Figure 17), DOC could be used to determine if chlorine odours are likely to be detected, however, above this point it may be unreliable as an indicator. This finding is most probably due to the changing composition of the organic matter at higher levels of DOC as indicated by the increase in SUVA to above 5 L.m/mg.

GVW undertakes DOC testing on a monthly basis as part of their routine water quality monitoring program. This would not give the operators real time data and ease of indication where a potential odour issue may occur. GVW should investigate the benefits of monitoring for DOC, in both the raw and the clarified water, either through the use of an online DOC meter or the use of UVA as a surrogate.

4.3.2 Final water quality parameters

Figure 18 shows the relationships determined between the count of chlorine and earthy /musty odours and the free chlorine residual detected at the inlet (point of disinfection) and the outlet of the CWS.

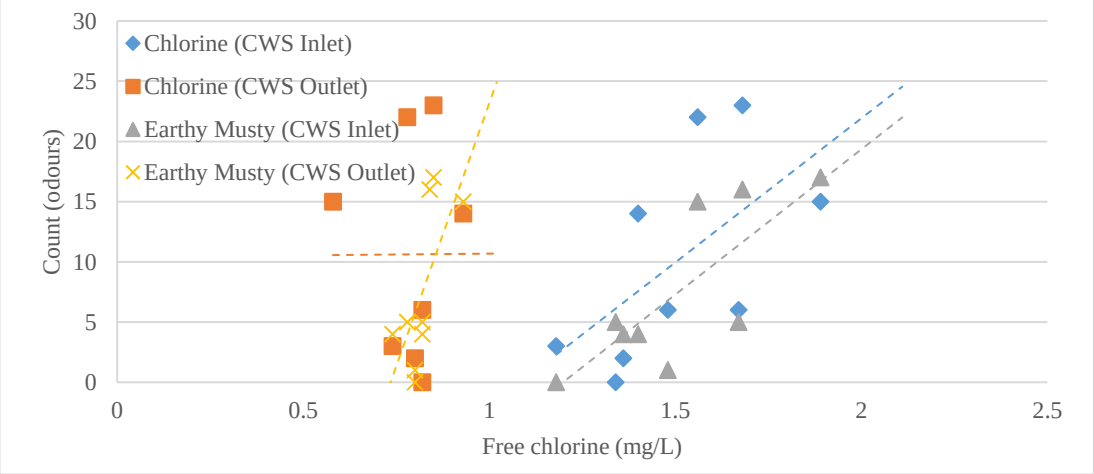


Figure 18: The count of chlorine and earthy /musty odours detected as a function of free chlorine at the inlet and outlet of the CWS

The Pearson's correlation coefficients (Table 10) for the data shown in Figure 18 indicates that there is a strong linear relationship at $p \leq 0.05$ between the count of earthy /musty odours and free chlorine residual at both the inlet and outlet of the CWS. In addition to this there appeared to be a moderate relationship between the counts of chlorine odours detected against the free chlorine residual at the inlet of the CWS. Equally, there appeared to be a weak relationship between chlorine residual at the outlet of the CWS and the count of chlorine odours detected.

Table 10: Pearson's correlation coefficient determined between free chlorine residual and the count of odours.

Correlation	Pearson's correlation coefficient (r)	Significance (p)	Degrees of Freedom
Chlorine odours – free chlorine inlet	0.598	0.044	19
Chlorine odours – free chlorine outlet	0.491	0.090	19
Earthy /musty odours – free chlorine inlet	0.784	0.006	19
Earthy /musty odours – free chlorine outlet	0.692	0.019	19

The data in Table 10 validates observations made in Section 4.1 that there is some unintended control with respect to taste and odour via the disinfection process. These results indicate that the detection of increasing free chlorine values at the disinfection point, the inlet to the CWS, could be used to predict if chlorine or earthy /musty odours may occur.

The data shows that there is a moderate but insignificant relationship between the outlet free chlorine residual and the number of chlorine odours detected in the reticulation system. This is in contrast to the data shown in Table 8 and Figure 11 which suggest that an increase in free chlorine residual at the outlet of the CWS would impact on the number of chlorine odours detected. As previously stated, if there is some unintended control around taste and odour through chlorination, the point of disinfection at the inlet to the CWS would be the only point of control. Hence, the outlet chlorine residual is entirely dependent upon the composition of the water and any reactions that are occurring within the CWS.

The correlation between the earthy /musty odours in the water reticulation system and the outlet free chlorine is expected to be due to the free chlorine masking any present earthy /musty odours. As any free chlorine present dissipates these earthy /musty odours can recur.

The other relationship of note was between total THMs and earthy /musty odours (Figure 19). The count of earthy /musty odours rose as the concentration of THMs increased.

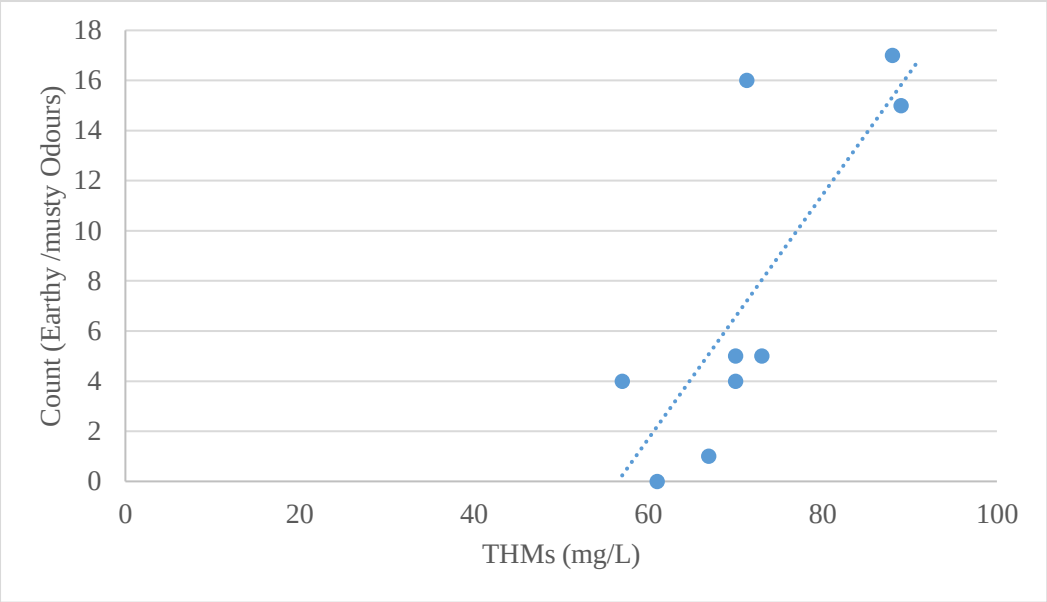


Figure 19: Correlation between the count of earthy /musty odours and total trihalomethanes

The relationship shown in Figure 19 is supported by the Pearson's correlation ($\rho = 0.788$, $\alpha = 0.006$). This result was unexpected as all THMs (bromoform, chloroform, dibromochloromethane, bromodichloromethane) have a characteristic sweet medicinal odour (Suffet, Mallevialle & Kawczynski 1995). It is likely that the odours forming were not as a result of the THMs, but rather as a result of residual NOM within the system. THMs are the result of a reaction between free chlorine residual and some organic compounds within the water (Twort, Ratnayaka & Brandt 2000). Depending on the composition of the NOM, the odours occurring are as a result of the unreacted organic compounds available. This is further indicated by the low concentrations of THMs shown in Figure 19, which is unusual given the high concentration of DOC within the raw water. As mentioned in Chapter 2, there is a clear relationship between the concentration of NOM present and the volume of THMs formed (Deborde & Van Gunten 2008).

4.4 Summary

The main odours identified were earthy /musty and chlorinous. These were not obviously attributable to any particular chemical compound such as geosmin or MIB. This finding is in line with much of the literature which suggests that taste and odour events can be difficult to attribute to specific compounds. This may be due to the presence of multiple offending compounds where their concentrations are below the analytical level of detection (Burlingame, Doty & Dietrich 2017). The data gathered, however, indicates that some basic water quality parameters could be used to identify when earthy /musty and chlorine odours are likely to occur. In particular the use of a bench-top UV spectrometer and the installation

of an online DOC analyser could be used to determine the SUVA value in a timely manner. This additional analysis would assist in the operation of the WTP as well as allowing the operator to adjust the WTP process appropriately to decrease the odours. Further education of the operator around chlorine control could also be used to identify if there will be a potential odour issue in the reticulation system. THMs are only analysed monthly and are determined after the fact, and are therefore not a useful tool to identify if a taste and odour issue will occur.

The parameters identified as correlating to odours detected can be attributed to NOM within the raw water and the use of free chlorine within the reticulation system. Therefore, it is recommended that GVW pay greater attention to the organic loading of the raw water. In addition to this it is also recommended that greater regard to NOM be given when considering the chlorine dose rates for disinfection.

The next chapter details the assessment of chemical coagulation to potentially improve the odours determined by the panel.

5 Chemical coagulation for odour improvement

The findings in Chapter 4.1 explored the relationships between water quality parameters which indicate the presence of NOM against identified odours. These relationships gave some indication that the presence of NOM could be the cause of the odours present. As organic matter is traditionally removed through chemical coagulation, optimisation of the coagulation process was undertaken to improve taste and odours (Drikas 2003). Additionally, as ferric sulphate and ACH have been shown to be more effective at removing organic matter through coagulation (Jarvis et al. 2012), these coagulants were trialled to understand their impact on taste and odours.

5.1 Raw water quality analysis

As many of the parameters that could be used to identify a taste and odour issue were associated with the raw water (SUVA, UVA and DOC), further understanding of the raw water was required to optimise the treatment process for taste and odour reduction. The use of these parameters identified as potentially indicative of odour detections occurring were considered in the optimisation.

As mentioned in Chapter 1, the catchment that feeds Euroa WTP is a combination of forested and cleared agricultural land that is used for mixed rotational farming between sheep and annual crops. Due to the historic practices associated with the operation of the storages, Mountain Hut water tends to be a mixture of water from Waterhouse and Abbinga Reservoirs. The contribution of each reservoir to the make-up of Mountain Hut can be dependent upon weather (including rainfall and stream-flow), operator preference and treatability. Table 11 shows the key organic indicators for the three raw water storages at Euroa.

Table 11: Water quality parameters for Raw water inlet /Mountain Hut, Waterhouse and Abbinga Reservoirs (n = 16)

	Raw water inlet/ Mountain Hut Reservoir		Waterhouse Reservoir		Abbinga Reservoir	
	Average	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
DOC (mg/L)	11.4	3.69	14.8	1.79	11.2	2.60
UVA (/cm)	0.49	0.15	0.64	0.05	0.45	0.12
SUVA (L.m/mg)	4.92	1.63	4.44	0.47	4.54	1.32
pH	7.73	0.37	8.32	0.56	8.31	0.28

Waterhouse Reservoir Catchment is heavily forested with the feeder streams drying up in periods of dry weather. During wet weather, when these feeder streams are running, significant amounts of vegetation are washed into the storage. According to Lin (1977) decaying

vegetation is one of the more frequent causes of tastes and odours in drinking water, with earthy /musty odours being the main ones detected.

Anecdotally, when Waterhouse Reservoir water is being treated taste and odour complaints occur within a couple of days. Unfortunately, there is not enough operational data to cross check this against customer complaints. This observation is contradictory to the water quality parameters shown in Table 11 when considering the correlations determined in Chapter 4.3. The higher SUVA value shown indicates there should be fewer odours detected in the reticulation system. As the water from Waterhouse Reservoir is gravity fed to Mountain Hut Reservoir, this is likely to change the treatability of the water prior to entering the WTP, and so influencing the odours seen following the change.

Abbinga Reservoir is situated entirely within private farmland which explains the lower DOC and UVA levels as less organic matter finds its way into the water body. The SUVA levels for all three storages indicate a similar treatability for each.

Fluorescence EEMs were completed on a sample from each of the Reservoirs to understand the fluorescent NOM content. The FRI technique method (Chen et al. 2003) was used to quantify the visible fluorescent organic matter in each of the raw water storages. The spectral volumes were integrated under five EEMs regions (Table 12).

Table 12: EEMs regions used in the fluorescence regional integration technique (taken from Chen, et al., (2003))

Region	Description	Excitation	Emission
I	Aromatic Protein Group I	220 nm – 270 nm	280 nm – 330 nm
II	Aromatic Protein Group II	220 nm – 270 nm	330 nm – 380 nm
III	Fulvic Acid- Like substances	220 nm – 270 nm	380 nm – 550 nm
IV	Soluble microbial by-products	270 nm – 440 nm	280 nm – 380 nm
V	Humic Acid - Like substances	270 nm – 440 nm	380 nm – 550 nm

It should be noted that recent literature states that the regions given by Chen et al's method (2003) are not as clearly defined as initially thought, and that instead the regions tend to contain mixtures of the humic and fulvic acid like substances (Liu et al. 2011). However, for the purposes of this study, the Chen et al. method using regional integration was considered suitable.

The DOC, UVA and SUVA values for the three reservoir samples treated by EEMs are shown in Table 13.

Table 13: The DOC, UVA and SUVA values associated with the raw water samples treated to EEMs

	DOC (mg/L)	UVA (/cm)	SUVA (L.m/mg)
Mountain Hut Reservoir/ raw water inlet	7.3	0.59	7.6
Abbinga Reservoir	7.9	0.60	7.6
Waterhouse Reservoir	11.0	0.62	8.0

The results of these EEMs and the outcomes of the FRI can be seen in Figure 20 and 21.

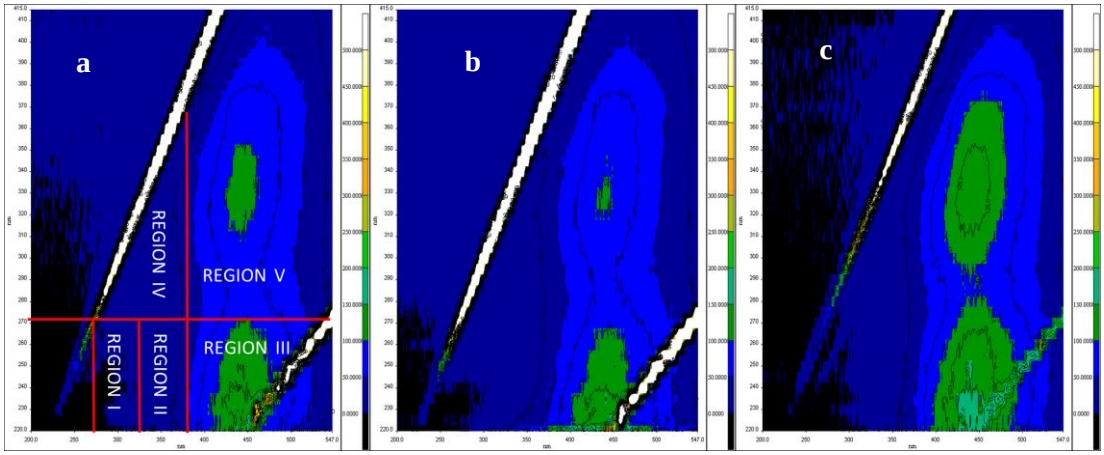


Figure 20: EEM spectra from 15/2/2017 of (a) raw water inlet /Mountain Hut Reservoir (b) Abbinga Reservoir and (c) Waterhouse Reservoir

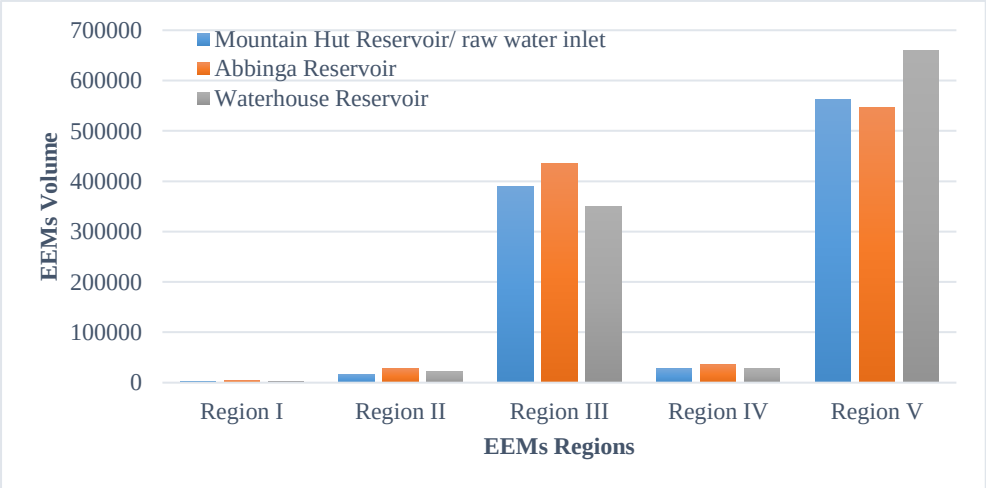


Figure 21: Volumes determined for each of the EEM spectral regions using the Chen et al (2003) method

Figure 20 and 21 show that the fluorescent organic matter in the raw water storages for Euroa is predominantly made up of humic acid - like substances (region V) and fulvic acid - like substances (region III). There is minimal fluorescence in regions I and II showing that there are few aromatic proteins similar to tyrosine (Region I) or tryptophan (region II). Region IV

shows some minor fluorescence indicating low levels of soluble microbial by-product - like compounds.

Figure 20 and 21 show that the EEM Spectra for humic and fulvic - like substances present in Mountain Hut Reservoir is between the EEM spectra for Abbinga Reservoir and Waterhouse Reservoir. This suggests that the Mountain Hut Reservoir sample is a mix of both Waterhouse and Abbinga which is representative for the operation of the storages previously mentioned. The EEM spectrum for Abbinga Reservoir shows less fluorescent humic – acid like substances than the other two storages and more fulvic acid - like substances. This likely relates to the catchment area which is private cleared farmland, this is also the likely reason for the greater volume of fulvic acid - like substances seen.

The catchment areas for both Waterhouse Reservoir and Mountain Hut Reservoir are heavily forested, with large amounts of native vegetation surrounding them and the tributary which feeds Waterhouse Reservoir. As noted earlier this tributary only flows during periods of wet weather and negatively impacts on the treatability due to the large volumes of vegetation that can be washed into the storage. This vegetation then decays, causing the water from Waterhouse Reservoir to be odorous. The influence of the vegetation in the storage is seen in the EEM spectra with the volume of humic acid - like substances being higher for Waterhouse than either Abbinga or Mountain Hut Reservoirs. This aligns with Lin's (1977) findings and the anecdotal taste and odour issues when treating water from Waterhouse.

The volumetric make-up of the water from each reservoir, reaching the Euroa WTP is unknown. Therefore to further improve the operability of the water treatment plant an increased understanding of the volumes of water transferred between the storages is required. It is recommended that flow monitoring be implemented and a water balance be completed to improve the ability to selectively withdraw water to improve the quality of water being treated.

Further analysis of the data for the combined raw water entering the treatment plant was undertaken using archived data from 2004 to 2015 (Table 14). It should be noted that some SUVA data was discarded due to very high readings (>20 L.m/mg) which appeared to be as a result of an error associated with low DOC (< 3 mg/L) and high UVA (> 0.78/ cm) values which were more indicative of the treated Euroa Water.

Table 14: Average and standard deviation of NOM indicators

	Average	Standard Deviation	Minimum	Maximum	N
True Colour (Hazen)	154	84	20	550	173
Dissolved Organic Carbon (mg/L)	9.2	3.9	3.0	21.0	57
UVT (%)	27.5	10.8	8.0	55.0	57
SUVA (L.m/mg)	7.4	4.3	3.9	11.7	54
pH	7.2	0.4	6.0	10.0	244
Turbidity	15.0	11.6	0.3	90.0	216

These results show the great variability of the raw water, especially in colour, turbidity and SUVA values. This supports the site operator observations that the raw water is variable and can change quickly. The high SUVA values are consistent with the findings shown in Figure 21 indicating the high content of humic substances. The data showed that the water was high in DOC, colour, and low in turbidity over the period as shown by the picture of a typical raw water sample shown in Figure 22.

Figure 22: Raw Water Sample from Euroa WTP (Taken 15/02/2017)

In order to improve the operation at Euroa WTP the operator needs to have an improved understanding of the nature of the NOM within the raw water. DOC is difficult to test for by the WTP operator as the DOC analysis available to GVW takes time. At present DOC is sent to SGS Laboratories for testing and is required for SUVA, which is the most practical indicator to understand the nature of NOM, and as shown in Chapter 4. As bench-top determination of UVA is readily available at Euroa WTP, this was used to give an indication of DOC through this study. Figure 23 shows the relationship that could be used to estimate DOC from UVA.

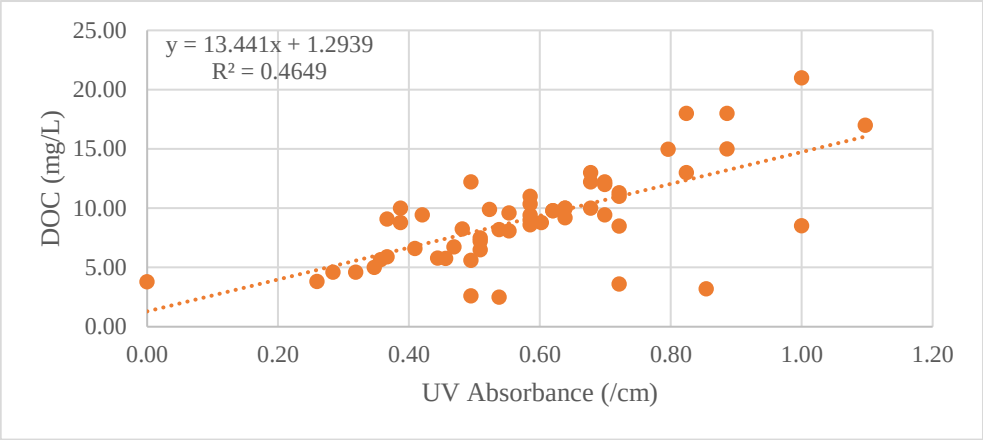


Figure 23: Relationship between raw DOC and UV absorbance

A benchtop UVA meter could be used in the optimisation of the process with respect to organic matter. As noted previously, it is recommended that GVW invest in an online DOC analyser which could be used in conjunction with the bench top UVA meter on an ongoing basis. The use of DOC and UVA by the WTP Operator would allow the coagulation process to be optimised with greater respect to the NOM present, and potentially be indicative of where odours may occur.

Further EEM spectra were determined for the inlet water to the WTP to determine the composition of the fluorescent organic matter. The data shown in Figure 24 were taken between May 2015 and April 2017 and show the EEM spectral volumes for each region of the raw water samples taken from the inlet to the WTP. The EEM volumes shown for region III and V demonstrate the fluorescent organic make-up of the water is predominantly humic and fulvic acids – like substances.

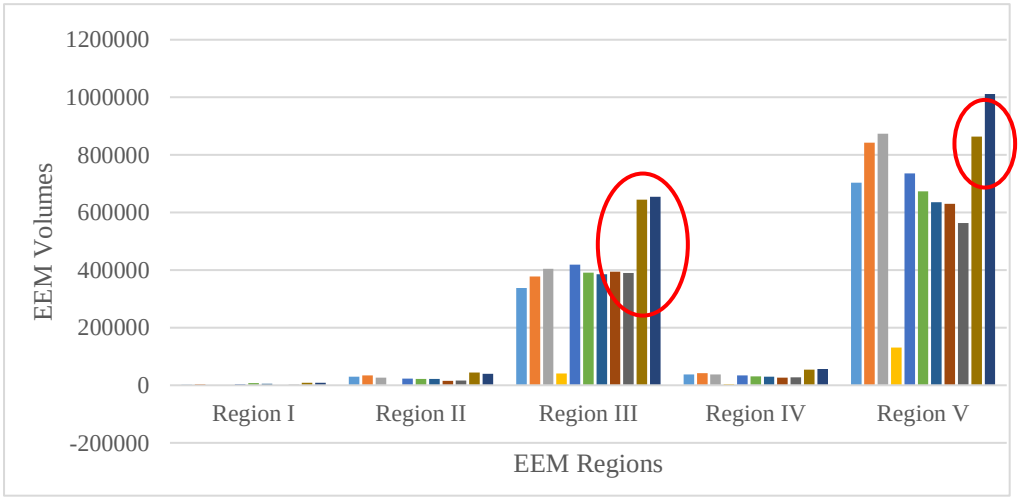


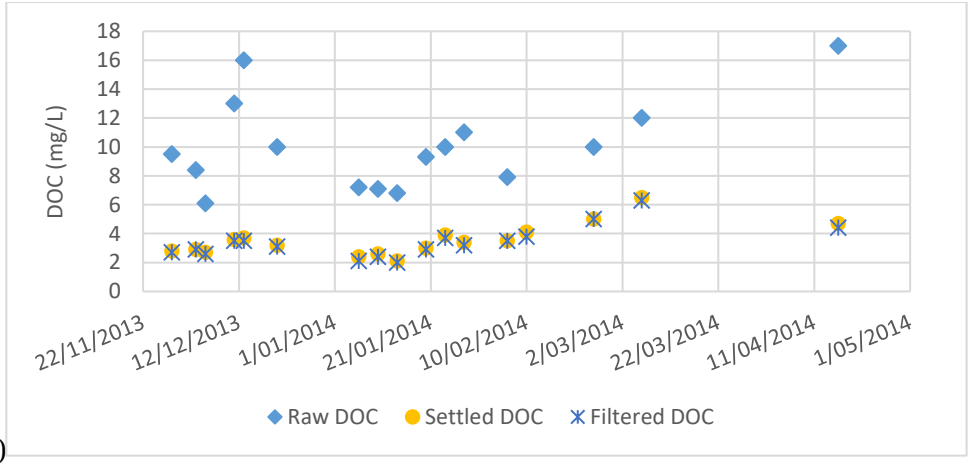
Figure 24: EEMS volume make-up of eleven raw water samples in each region based on the FRI technique method detailed by Chen et al (2003)

The results in Figure 24 show the fluorescent fulvic acid- like substances volumes were reasonably consistent with the exception of the two outliers (taken 14/4/2017 and 28/4/2017 and are highlighted). In the days prior to these two samples being taken there was significant rainfall in the catchment with 20 mm and 50.8 mm falling, respectively. The humic acid – like substances volume following the 50.8 mm rainfall increased which was expected as vegetation, and associated dissolved NOM, would have been washed into the Reservoir following the rainfall. Regions I, II and IV show very little fluorescence in comparison to regions III and V. Regions II and IV do have a slight increase around the same time as the rainfall, which could be due to rainfall with biological matter being washed in or algal activity in the catchment. There was no obvious algal bloom at this time but the complexity of the catchment may have meant this was not detected. The humic acid - like substances (region V) have more variable volumes than the other four regions.

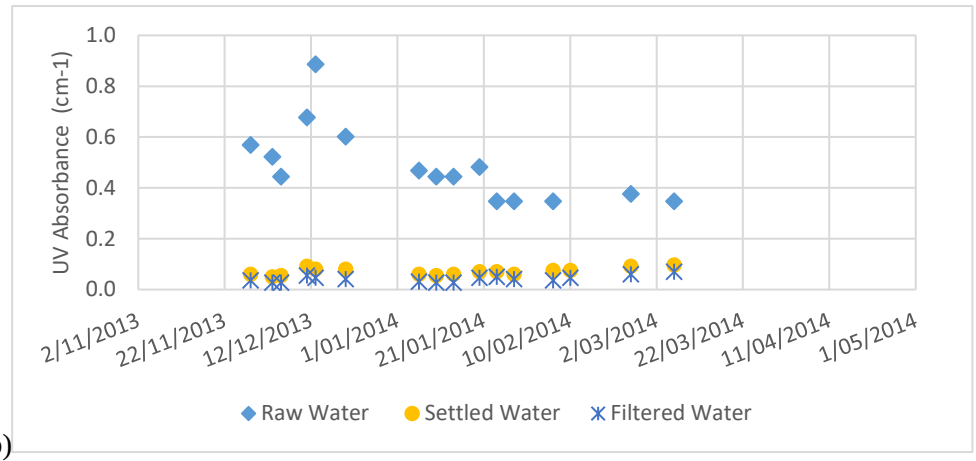
Based on the results from the individual water storages and the high SUVA values, the EEMs results at the inlet were as expected with the fluorescent organic composition shown as being predominantly humic and fulvic acid – like substances.

5.1.1 Water Treatment Plant Operation

In order to understand the current operation of the Euroa WTP, UVA and DOC were used as indicators for the organic content within the raw water. Figure 25 shows the changes in DOC (chart a) and UVA (chart b) across the treatment process.



(a)

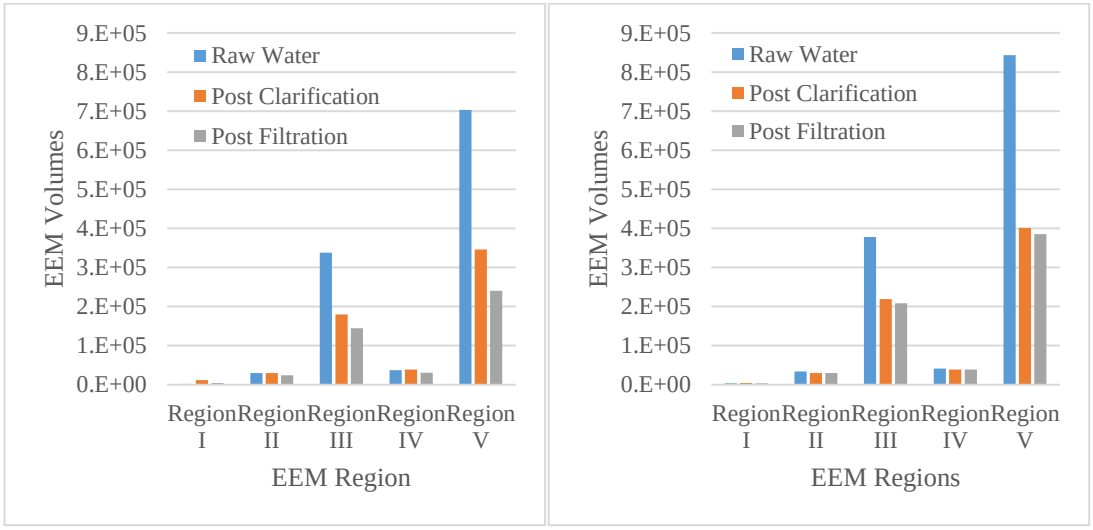


(b)

Figure 25: Reduction in DOC (a) and UVA (b) across the treatment process

The major trend of interest was that the bulk of the DOC removal and UVA reduction occurred through the coagulation and clarification process (settled water). There appeared to be minimal further DOC removal through the filtration process (average removal = 0.7 mg/L, standard deviation = 0.08 mg/L, N = 14) and only a minor reduction in UVA across the filters (average removal = 0.03 $cm^{-1,}$ standard deviation = 0.006 cm^{-1}, N = 18). This suggests that there is minimal organics removal through the filtration process.

EEM spectra were determined for samples taken on the 6/5/2015 and the 20/5/2015 to further understand the changes through the process. The volumes of fluorescent organic matter through the raw water, post clarification and post filtration are seen in Figure 26.



(a) (b)

Figure 26: EEM spectral volumes across the WTP process on the 6/5/2015 (a) and the 20/5/2015 (b)

The EEM spectral volumes shown in Figure 26, in particular the volumes seen in regions III and V, show that the key removal step of the fluorescent fulvic and humic - acid like

substances is through the clarification process (settled water). In the sample taken on the 6/5/2015 there was a further reduction of the fluorescent humic and fulvic acid - like substances through the filtration process. However, in the 20/5/2015 sample, there was only a small reduction between the clarification (settled water) and the filtration process. This supports the results in Figure 25 which show that the DOC removal and UVA reduction occurs predominantly in the clarification process (settled water) with only minimal further removal/reduction in the filtration process. This is further seen in the water quality parameters associated with the samples subjected to EEM spectroscopy. These are shown in Table 15.

Table 15: Parameters for the samples subjected to EEMs

	Raw Water			Settled Water		Filtration	
	SUVA (m/L-mg)	**DOC mg/L**	**UVA /cm**	**DOC mg/L**	**UVA /cm**	**DOC mg/L**	**UVA /cm**
6/5/2015	6.108	7.40	0.452	3.88	0.065	3.75	0.045
20/5/2015	5.728	10.91	0.625	3.08	0.064	2.91	0.061

Based on this data it is clear that the main removal process for organics is coagulation with little further removal occurring in the filtration process. Therefore, in order to improve the removal rates of organics, the coagulation process was focussed on.

5.2 Comparison of coagulants

Coagulation with ferric sulphate and ACH was compared with aluminium sulphate, which is currently used, for organics removal. UVA and DOC were used as measures of effectiveness for organics removal. Jar testing was completed to mimic the existing plant conditions, with odour testing performed to determine the improvements in odour. EEMs were undertaken to understand the changes in fluorescent organic makeup and DOC and UVA removal.

5.2.1 Comparison of coagulant dose rates

This section reviews the outcomes of jar tests using all three coagulants and compares the chemical dose rates. The results from the jar tests can be found in Appendix 2.

5.2.1.1 Aluminium sulphate jar tests

Historically turbidity and colour have been used as a basis for determining the aluminium sulphate dose. Discussions with the operator indicated that there was an understanding of the organics present but, these were not considered when the dose rate was set. Further investigation into the historic dose rates showed that the dose set by the operator had a closer affinity to the SUVA values of the raw water than the colour or turbidity. The correlation between colour and the alum dose rate was low with low significance when using Pearson's correlation coefficient ($r = 0.16$, $p = 0.32$). Similarly, when reviewing the influence of turbidity on the coagulant dose the correlation was low with low significance ($r = 0.178$, $p=0.29$).

Discussions with the operator suggest that following the jar tests being completed the dose rate was further tweaked based on their knowledge of the system. This suggests that although there was no conscious consideration given to the organics their presence had some influence on the dose rate setting. The Pearson's correlation coefficient between the aluminium sulphate dose rate and SUVA showed the relationship was considered moderately high ($r = 0.63$, $p = 0.02$) which would suggest that the operator takes into consideration organics as a basis of the dose rate being set.

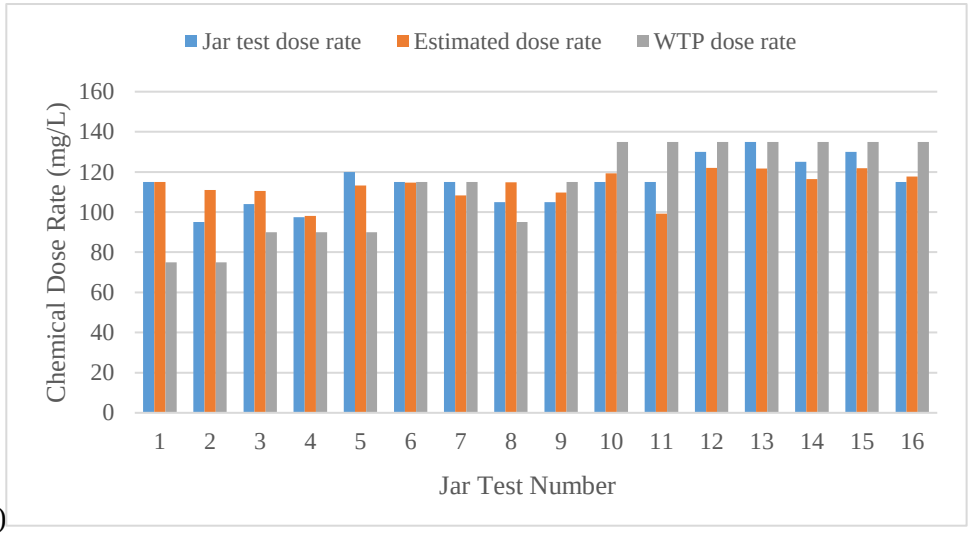
GVW procedures recommend that with changing water quality the raw water should be jar tested to determine the optimal dose. With the variation seen in the raw water at Euroa WTP this can be considered as time consuming and where there are conflicting priorities, these may not be completed. A multivariate regression was completed using the turbidity and UVT results from eleven jar tests completed between May 2015 and November 2015 to develop an algorithm to assist the operators during periods of variable water quality. This is shown in Equation 4. This was validated further and compared to subsequent jar tests. These results are shown in Figure 27.

$$\textbf{Alum Dose } \left(\frac{\textbf{mg}}{\textbf{L}}\right) = \mathbf{141.40 - 0.86\ UVT_{raw} - 0.71\ Turbidity_{raw}} \quad \textbf{Equation 4}$$

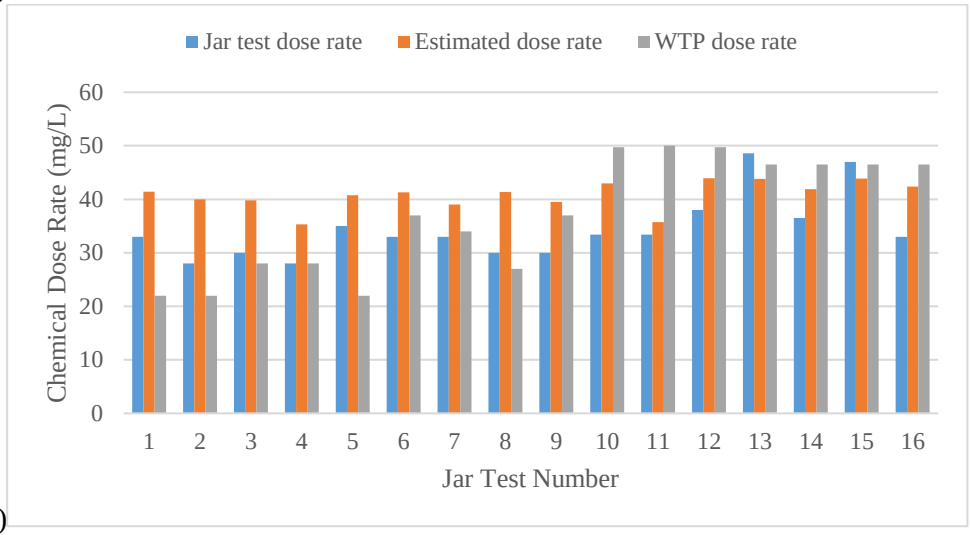
The target pH at the WTP is set at 6.2 which requires pH correction using caustic soda. This was also used as the target for the jar tests using aluminium sulphate. The dose rates for the jar tests were based on the amount of alkalinity consumed by the aluminium sulphate (0.45 mg consumed as $CaCO_3$) and the amount of alkalinity added by the caustic (1.25 mg added as $CaCO_3$) in line with the guidance in Murray & Mosse (2015). This relationship is shown in Equation 5.

$$\textbf{Caustic Dose } \left(\frac{\textbf{mg}}{\textbf{L}}\right) = \frac{\textbf{Alum Dose Rate x0.45}}{\textbf{1.25}} \quad \textbf{Equation 5}$$

Equation 4 was validated further and compared to the subsequent jar tests. These results are presented in Figure 27, which shows the comparison between the jar tested aluminium sulphate and caustic dose rates, the operator set dose rate and the estimated dose rate. The estimated dose rates are based on Equations 4 and 5.



(a)



(b)

Figure 27: Comparison of aluminium sulphate dose rates (a) and caustic soda dose rates (b)

The variability seen between the WTP dose rates, the jar tested dose rates and the estimated dose rates shown in Figure 27 demonstrates that the estimated dose rate from Equation 4 should be used as a guide only. The accuracy of this could be improved by adding more jar test data into the regression used. These dose rates tended to be more consistent when compared to the best dose rates from the jar tests. Similarly, the estimated caustic dose rate based on alkalinity was much higher than either the actual dose rate or the jar tested caustic dose rate. The aluminium sulphate dose rate set by the operator was sometimes higher than both the optimal jar tested dose and the estimated dose. This was expected due to the operational practices around overdosing to combat changing raw water quality.

5.2.1.2 Ferric sulphate jar tests

Ferric sulphate has been shown to have greater DOC removal capacity than aluminium sulphate and is normally used in waters with high organic loading (Matilainen, Vepsalainen

& Sillanpaa 2010). In general, a lower dose rate is required for ferric sulphate than for aluminium sulphate, however it has been known to form greater amounts of sludge and waste water (Twort, Ratnayaka & Brandt 2000). Figure 28 shows the optimal ferric sulphate doses from the jar tests, which were completed between August 2016 and April 2017.

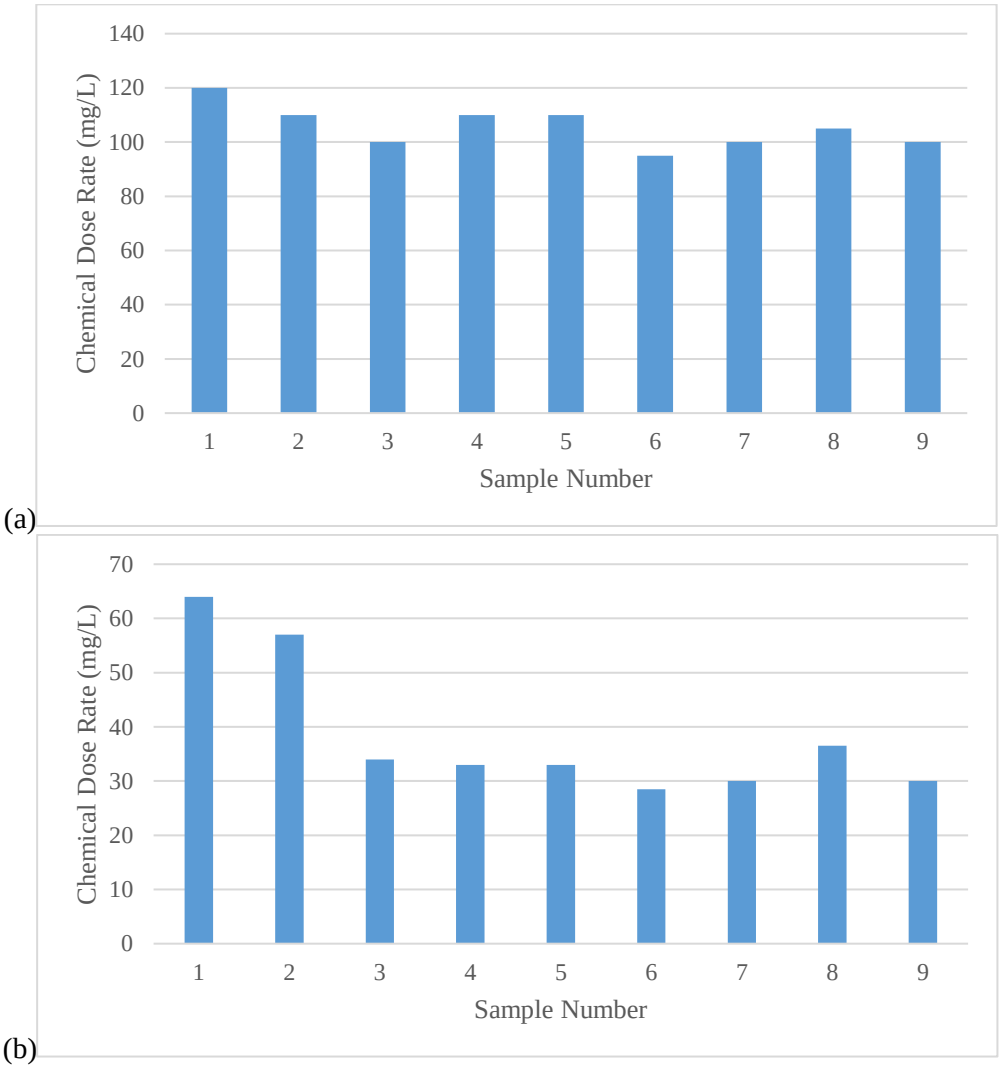


Figure 28: Ferric sulphate (a) and caustic soda (b) jar tested dose rates

In the jar tested samples seen in Figure 28 the target pH for coagulation was pH 5 which is within the optimal range (pH 4.8 – 6) for organics removal with ferric sulphate (Matilainen, Vepsalainen & Sillanpaa 2010). Coagulation was conducted at a lower pH than the aluminium sulphate jar tests (target pH = 6.1), which resulted in a lower caustic soda dose rate for pH correction compared with using aluminium sulphate. The literature around coagulation suggests that DOC removal should be between 29 % and 70 % using ferric sulphate at a lower pH (Matilainen, Vepsalainen & Sillanpaa 2010).

5.2.1.3 Aluminium chlorohydrate jar tests

ACH was selected as a third option as it is used as an alternative to aluminium sulphate at other GVW WTPs. It is considered to be more effective over a broader pH range which makes it simpler to use than aluminium sulphate or ferric sulphate (Matilainen, Vepsalainen & Sillanpaa 2010). The general operational rule of thumb is that the ACH dose is one third of the aluminium sulphate dose rate which is due to the higher concentrations of Al_2O_3 present (23-25% and 7-9%, respectively) which is the basis of floc formation (Murray and Mosse 2015). The ACH dose rates from jar tests completed between November 2015 and April 2017 are shown in Figure 29. No pH correction was required so caustic soda dose rates were not reviewed.

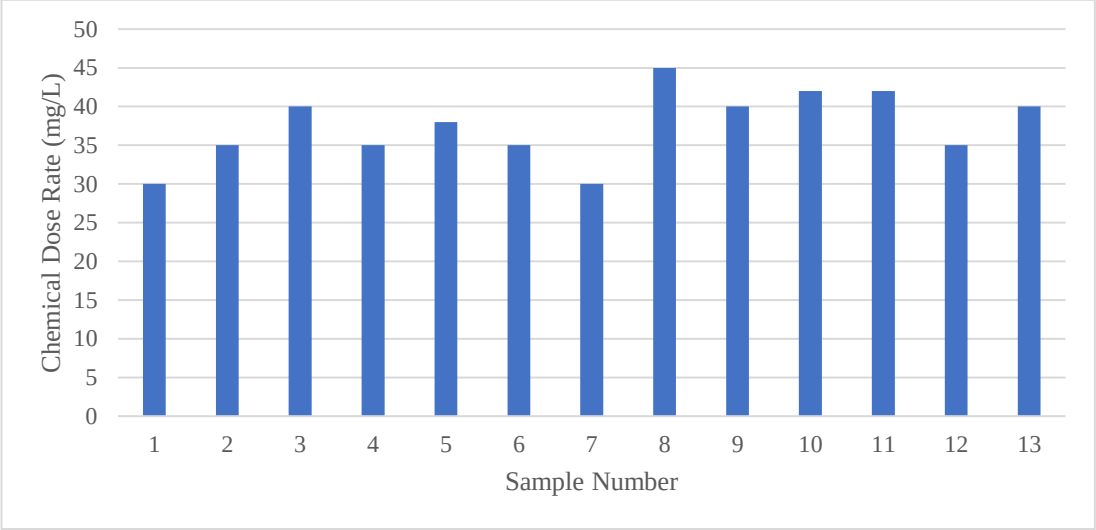


Figure 29: ACH jar tested dose rates.

The design of the clarifier at Euroa WTP requires a heavy floc blanket to be effective. The sludge produced as a result of ACH coagulation was light in nature and slow to settle. The existing site polymer which is used as a coagulation aid (Flopam 4190 PWG) was trialled to increase the density of the sludge and allow for settlement. The polymer dose rates ranged from 0.1 – 0.4 mg/L. Although this worked to some degree, the maximum recommended polymer dose rate of 0.2 mg/L (Murray and Mosse 2015) was exceeded and the sludge produced was still slow to settle with floc still in suspension after 20 minutes. Although there was some improved settling ability, it is unclear if the sludge produced would work effectively in the Euroa clarifier.

5.2.2 DOC removal and UVA reduction

The percentage DOC removal and UVA reduction were determined for all the coagulants trialled and compared to the DOC and UVA reductions at the WTP. These results are shown in Table 16 and 17, respectively.

Table 16: A comparison of DOC removal rates as percentage between the WTP and the alternative coagulants

	WTP	Aluminium Sulphate	Ferric Sulphate	ACH
Average (%)	57	55	72	59
Standard Deviation (%)	10	9	7	13
Minimum (%)	23	27	57	33
Maximum (%)	72	65	80	72
Number of Samples	33	15	9	12

The ferric sulphate and ACH jar test results show greater average DOC removal than obtained in the WTP and the aluminium sulphate jar tests. The DOC removal rates for the ferric sulphate samples were fairly consistent.

The DOC removal with ACH showed that although there was a high average, the variability was also high with values ranging from 33 % up to 72 % with a high standard deviation. This indicates that there may be other interactions occurring during the jar testing process that inhibit DOC removal.

The aluminium sulphate and WTP DOC removals were consistent with each other, with the WTP showing a slightly greater variability and a higher standard deviation. As the clarifier is not covered, and outside factors such as the weather can impact on the operation, it is likely that the variation seen is influenced by the clarifier operator. All of these results are in line with literature values for DOC removal, however the variability of the DOC removal by the ACH is unexpected and further investigation could be considered as a subsequent step to this case study.

The UVA reduction rates were very similar between the WTP and the three jar tested coagulants. These results are shown in Table 17.

Table 17: A comparison of UVA reduction rates in percentage between the WTP and the alternative coagulants.

	WTP	Aluminium Sulphate	Ferric Sulphate	ACH
Average (%)	84	85	85	82
Standard Deviation (%)	9	6	8	8
Minimum (%)	41	65	71	66
Maximum (%)	91	91	92	93
Number of Samples	36	15	9	13

The results in Table 17 show the consistency of UVA reduction across all the jar tests and the WTP. The average reduction in UVA using ACH was slightly lower than the other coagulants indicating some residual compounds in the coagulated water that absorb at 254 nm, this may also be a cause for the lower DOC removals seen. However as this is only a small difference it is not considered to be an issue for GVW.

The results in Table 16 and 17 indicate that for DOC removal and UVA reduction respectively, ferric sulphate is the preferred option.

5.2.3 Fluorescence excitation emission matrix spectra

EEMs were completed and compared to understand the changes in the content of fluorescent organic compounds. The date of samples analysed as well as the DOC, UVA and SUVA values are shown in Table 18.

Table 18: The dates, DOC, UVA and SUVA values from the samples with EEMs determined

	DOC (mg/L)	UVA (/cm)	SUVA (L.m/mg)
21/02/2015	9.86	0.64	6.47
6/05/2015	8.15	0.45	5.55
20/05/2015	9.80	0.63	6.38
25/11/2016	9.26	0.37	3.96
6/01/2017	10.0	0.89	8.86
11/01/2017	12.0	0.77	6.41
19/01/2017	11.0	0.82	7.49
31/01/2017	11.0	0.72	6.56
15/02/2017	7.30	0.59	8.01
13/04/2017	7.70	0.54	6.98
28/04/2017	10.0	0.66	6.58

The volumes of fluorescent organic matter from the raw water, the WTP and each of the chemical coagulants used are shown in Figure 30. Full EEMs spectra and volumes can be found in Appendix 3. Figure 30 (a) shows the EEM volumes for the raw water samples, Figure 30 (b) shows the EEM volumes for the WTP sample. Figure 30 (c), (d) and (e) show the EEM volumes for the aluminium sulphate jar tested samples, the ferric sulphate jar tested samples and the ACH jar tested samples respectively. Samples were collected and analysed between May 2015 and April 2017.

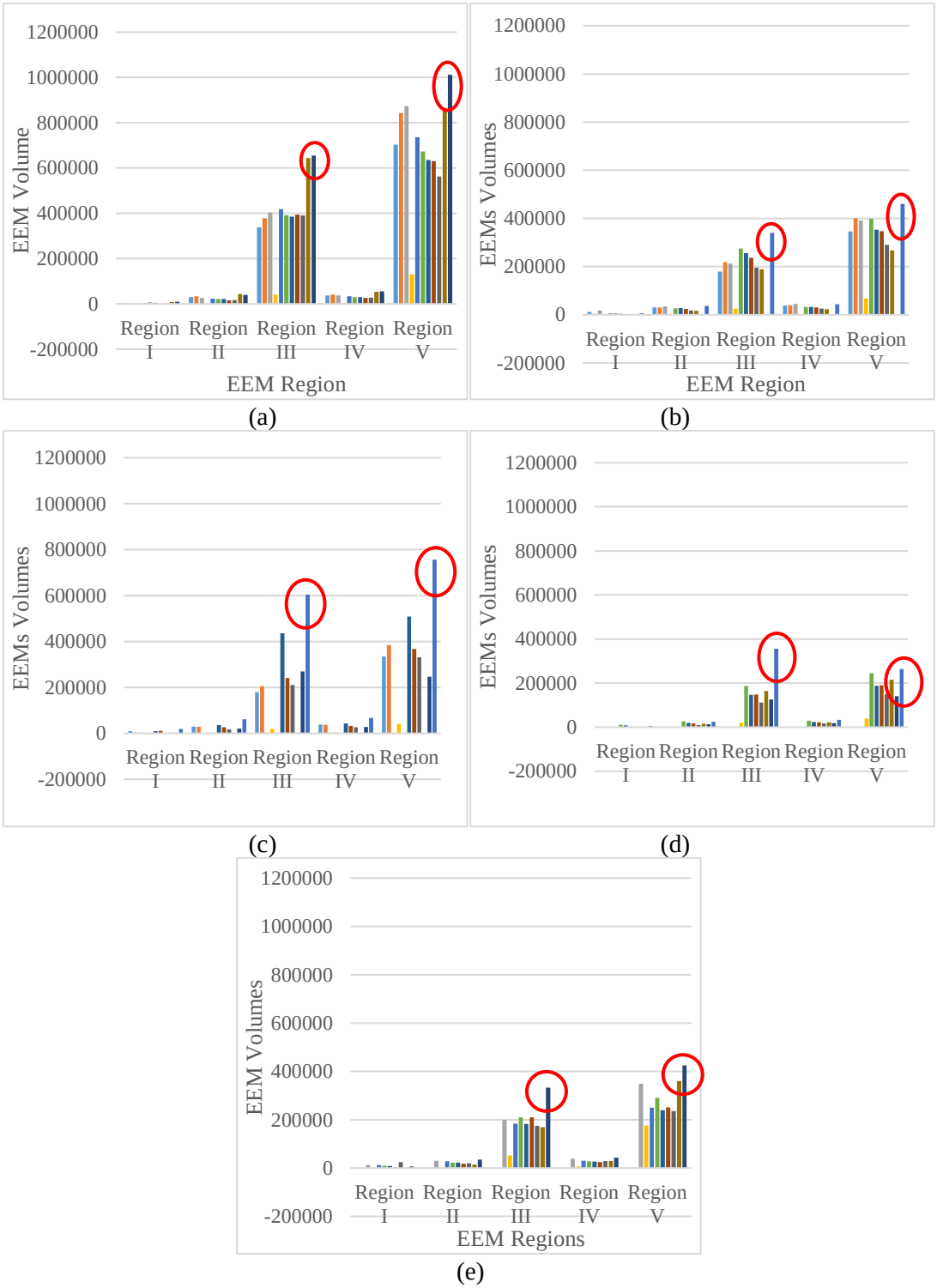


Figure 30: EEM volumes from the raw water (a), the WTP (b), aluminium sulphate jar tests (c), ferric sulphate jar tests (d) and ACH jar tests (e)

Fluorescent regions I, II, and IV show little discernible difference across all coagulants. Comparing regions III and V there is considerably less fluorescent organic matter in the ferric sulphate and ACH jar tested samples than in the WTP or the aluminium sulphate jar tested sample in comparison to the raw water samples. Free aluminium (Al^{3+}) has been known to bind humic substances at around the pH of the aluminium sulphate jar tests (~pH 6) (Umar,

Roddick & Fan 2014). There was some variability seen with the dosed pH (between pH 4.5 and pH 7) of the jars which may have led to some humics being bound and increasing the fluorescence, which could explain the variability seen in Figure 30 (C).

Looking at regions III and V, in all the EEM spectra shown in Figure 30 there is a spike which is highlighted on each figure. This spike coincided with the rainfall event on the 28/04/2017 mentioned in Section 5.1. With the ACH and ferric sulphate treated samples from this event, the volume of the humic acid - like substances was less than the fulvic acid - like substances which would indicate that the humic acid - like substances in the raw water following rainfall are more readily removed through coagulation using ferric sulphate and ACH than the fulvic acid-like substances. The aluminium sulphate and the WTP samples do not have the same trend. Unfortunately, there was no other significant rainfall event that coincided with the samples being taken to confirm if this is a normal occurrence.

Across all the spectra shown in Figure 30 the EEM volumes in each region from the ferric sulphate treated samples appear to be lower than those for the other coagulants used. The humic acid – like substance removal using ACH as a coagulant appears to be similar to the ferric sulphate. The samples taken following the rainfall event were further analysed using LC-OCD. These results are further discussed in 5.2.4.

5.2.4 Further organic analysis completed on a single sample

For the set of samples jar tested on the 28/4/2017 further organic analysis was completed. LC-OCDs, EEMs, and DBP formation were determined. Details of the DOC and UVA values associated with the samples which had further analysis undertaken are shown in Table 19. It should be noted that the aluminium sulphate dose rate was different to the WTP coagulant dose rate. This accounts for the difference in residual DOC between the two samples.

Table 19: DOC and UVA values of the variously treated samples which had further organic analysis

Sample	DOC (mg/L)	UV Absorbance	DOC Removal (%)	UVA Reduction (%)
Raw Water	10.0	0.66	-	-
WTP	4.4	0.15	56	78
Aluminium Sulphate	5.7	0.15	43	76
Ferric Sulphate	2.7	0.07	73	89
ACH	3.1	0.04	69	92

5.2.4.1 Liquid chromatography-organic carbon detection

LC-OCDs were completed on the set of jar tested samples shown in Table 19. The LC-OCD process separates DOC into five different chromatographic fractions. These are biopolymers

(>20,000 Da), high molecular weight (HMW) humic /like-substances (1000 - 20,000 Da), building blocks (300 – 500 Da) low molecular weight (LMW) acids and humic substances (<350 Da) and LMW neutrals (<350 Da) (Huber, et al., 2011).

These data are shown in Figure 31 and the findings confirm those from previous analyses. Full details of the DOC values for the different fractions can be seen in Appendix 4.

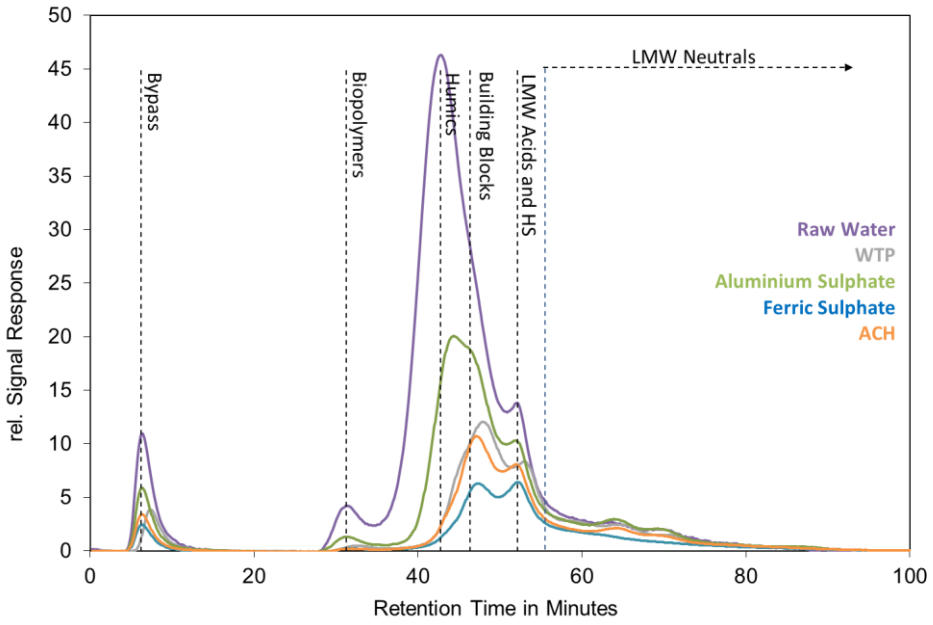


Figure 31: Organic carbon detection (OCD) outputs for liquid chromatography

The analyses indicate that the raw water contains predominantly humics with removal occurring for all coagulants. The ferric sulphate and ACH treated samples had the lowest amount of humics which is consistent with the higher DOC removal rates and the EEM results in Chapter 5.2.3. The concentration of humic substance shown in the WTP treated sample was consistent with the DOC removal rates shown in Table 19. The aluminium sulphate treated sample was shown to have the highest concentration of humic substances remaining following coagulation and was consistent with the low DOC removal rate shown in Table 19. However, despite the low DOC removal rate, there still appears to be a significant reduction in the humics. This data validates the previous findings indicating that the predominant removal pathway of the NOM in the samples was through coagulation.

Figure 31 indicates that the coagulation processes using ACH and ferric sulphate predominantly remove the larger molecular weight substances such as biopolymers and humics, with the residual DOC being made up of building blocks and LMW acids and LMW neutrals. The WTP sample was shown to be similar.

The residual DOC after coagulation with aluminium sulphate treated sample was predominantly humics, with very little removal of the other organic substances.

Figure 32 shows the outputs of the UV detection (UVD) for the liquid chromatograms. These results are very similar to those with DOC detection.

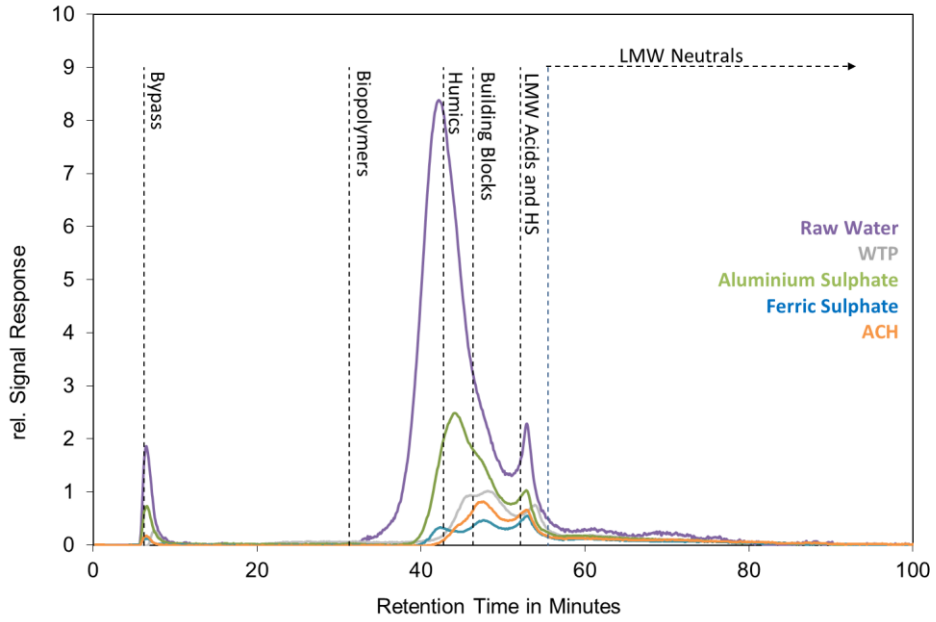


Figure 32: UV Detection (UVD) outputs at 254 nm from liquid chromatography

Similar to the OCD outputs the aluminium sulphate sample showed the least reduction for the humics despite having a similar UVA reduction to the WTP sample. The UVA reduction in the ACH treated samples was high in comparison to the WTP and aluminium sulphate treated samples and similar to the ferric sulphate treated samples. The sample taken from the WTP does not appear to be in line with the UVA reductions shown in Table 19. This may suggest that there may have been an inorganic interference during the analysis of UVA e.g., iron or manganese.

The ACH and the ferric sulphate treated samples show low UV absorbance with respect to all of the fractions, whereas the aluminium sulphate treated sample shows high UV absorbance in the humic substances region. These results are in line with the UVA reductions shown in Table 19.

Therefore, the LC-OCD outputs demonstrate that the predominant organics being removed through coagulation are humics.

5.2.4.2 Fluorescence excitation emission matrix spectra

EEMs were determined for the samples which had been analysed by liquid chromatography. The EEM volumes for each region are shown in Figure 33.

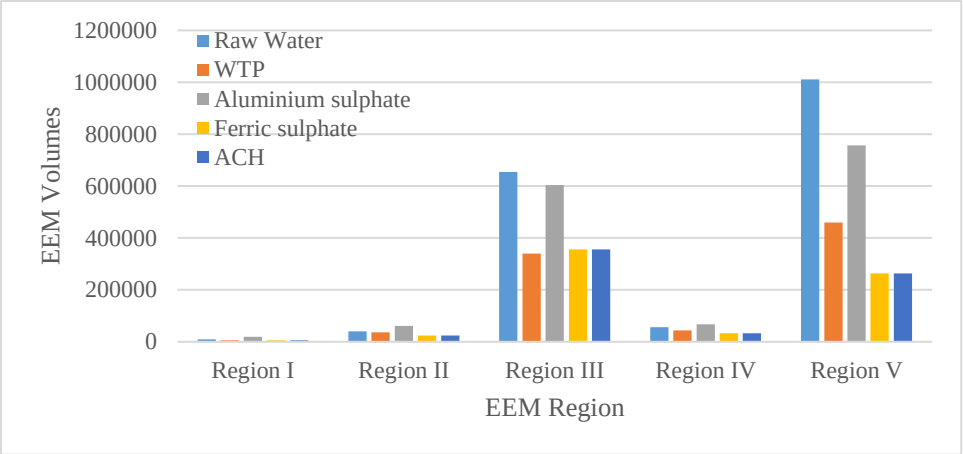


Figure 33: EEM spectra for the samples used in Section 5.2.4.1

The results in Figure 33 are consistent with the findings from the liquid chromatograms. The sample treated with aluminium sulphate showed limited removal of the fluorescent fulvic and humic acid-like substances. The WTP sample and the ACH treated samples show similar fluorescence in all regions. The ferric sulphate treated sample showed greater removal of the fluorescent humic acid-like substances than the other coagulants, however the fulvic acid-like substances were in line with those for the WTP and ACH samples.

5.2.4.3 Disinfection by product formation

The jar tested and WTP samples analysed by LC-OCD and EEMs were chlorinated and sent to SGS Laboratories for determination of all THMs and HAAs. Where a compound was detected these results are shown in Table 20. All other THMs and HAAs were below the limit of detection.

Table 20: The detected disinfection by product formation from chlorinated WTP and jar tested samples against the DOC percentage removal

	WTP	Aluminium sulphate	Ferric sulphate	ACH
Chloroform (µg/L)	20	19	12	1.2
Bromodichloromethane (µg/L)	1.6	1.7	2.8	<0.5
Dichloroacetic acid (µg/L)	26	14	5	<5
Trichloroacetic acid (µg/L)	14	7	<5	<5
DOC removal (%)	56	43	73	69

Although ferric sulphate coagulation gave the greatest DOC removal and the greatest reduction in humic substances, the ACH treated sample led to the lowest formation of DBPs. This was unexpected as the bulk of the literature suggests that the humic portion of NOM is the key precursor for THM formation. The results shown by the EEMs and the LC-OCDs

indicate that ACH treatment should have led to greater concentrations of DBPs. However as this was only a single sample, this should be taken into context.

The aluminium sulphate treated sample showed less DBP formation than the WTP sample despite the greater percentage DOC removal seen at the WTP which again was unexpected. This conflicts with the data shown in the LC-OCDs and the EEMs for these two samples which show that the concentration of humics present is much lower from the WTP. As discussed in Chapter 2, the reaction pathways associated with DBP formation can be complex, with many different aspects influencing the formation including the pH. As the pH can affect the DBP formation pathway, the higher pH in the WTP versus the aluminium sulphate jar tested sample (pH 6.7 and 6.1 respectively) may have contributed to the greater HAA formation.

5.2.5 Determination of the sludge volumes formed

Using a 1 L Imhoff cone the determination of sludge volumes was from the jar tests led to varying results. The density of the sludge produced from ACH was too low to settle sufficiently, even when polymer was added. The density of the aluminium sulphate sludge was also too low for full settlement to occur, even after one hour of settling time. As previously mentioned in Chapter 1, past issues with the floc blanket rising and causing carry over onto the filters meant that this was not a surprising result. The raw water parameters of these samples are the likely cause of the low density floc seen with the aluminium based coagulants, in particular the lack of particulate matter. The raw water parameters are shown in Table 21.

Table 21: Raw water parameters for the jar tests used in determining sludge volumes

Sample Number	Turbidity (NTU)	True Colour (Hazen)	UVT (%)	DOC (mg/L)
1	4.54	122	32	8.37
2	9.73	145	25	10.00

The low density floc produced by the aluminium based coagulants and the lack of particulate matter in the samples is consistent with the discussion in Chapter 2 which suggests that where NOM is present, the flocs formed may be weak and lower in density causing issues with solid - liquid separation (Jarvis, et al., 2004). The ACH samples had low density sludge which did not settle easily. Following the addition of the polymer there was still floc in suspension after an hours settling time.

The ferric sulphate floc, on the other hand, settled quickly and was dense and easy to measure, as stated in Chapter 2, the density of the floc formed can be impacted on by factors such as pH, in the case of the ferric sulphate treated samples, coagulation occurred at pH 5, as opposed to pH 6.1 for the aluminium based coagulants.

The results of the sludge production are shown in Table 22.

Table 22: Measured sludge volumes shown in cm^3 /2 L Jar

Sample Number	Aluminium Sulphate	Ferric Sulphate	ACH	ACH with 0.4 mg/L polymer added
1	60	95	20	30
2	90	100	70	50

The variation seen between the aluminium and ACH samples was as a result of the low density floc produced in the jars. Overall the results were as expected based on literature and industry knowledge, with ferric sulphate producing larger volumes of dense sludge and ACH producing low volumes of low density sludge. The feasibility of using ACH in the clarifier at Euroa would need further examination if it were to be implemented. ACH has been used successfully in similar clarifiers across GVW however the raw water at these sites tends to have a higher solids loading.

In order to replicate the higher solids loading seen at other GVW sites, a 10% suspension of bentonite was trialled to increase the solids loading in the raw water. The volumes of bentonite suspension added and the increase in turbidity are shown in Table 23. The ACH dose rate was not adjusted to meet the increased solids loading requirement, however this would improve the outcomes. The floc produced with the addition of bentonite was larger and denser. After 20 minutes of settling time, there was still some floc in suspension, however, there was a greater volume of floc that had settled when compared to an ACH jar with no bentonite added.

Table 23: Volumes of bentonite suspension added and the resultant turbidity value

	Raw water	Jar 1	Jar 2	Jar 3
Bentonite added (mL/L)	-	2	3	4
Turbidity (NTU)	8.9	13.4	14.8	17.8
ACH dose rate (mg/L)	32	32	32	32

Unfortunately, it was difficult to determine the volume of sludge produced using the Imhoff cone. As an initial indication the use of bentonite proved to successfully increase the density of the floc produced. Therefore, this could be considered to improve the compatibility of the ACH with the existing WTP process.

5.2.6 Comparison of odours from the jar tests and the WTP

Following jar testing, the jar which contained the best water quality had odours determined using the panel described in Section 4.1.1 to understand any changes in odours resulting from the use of the alternative coagulants. For each of the coagulants used, the counts for each odour detected by the panel are shown in Table 24.

Table 24: Count of odours detected against each coagulant following jar tests.

	Chlorine odours	Chemical odours	Earthy /musty odours	No odours	Other odours
Aluminium sulphate	3	4	36	28	4
ACH	2	4	20	25	3
Ferric sulphate	1	5	22	18	8
WTP	1	9	50	28	2
Shepparton RAC	50	8	7	13	1

Using the data from Table 24, a number of null hypotheses were developed and the Chi squared statistics determined (Table 25). The Chi squared test was used as it takes account of the different sample sizes for each of the data sets.

Table 25: Chi squared statistic and the null hypotheses based on odours detected

Null Hypothesis	Chi Squared Value (X^2)	Significance	Null Hypothesis Accepted?
The odour of the data sample type of chemical used is independent of the odour in the jar test samples	7.46	0.49	Yes
The odours of the data samples from the WTP are independent of the odour of the data sample from the jar test samples	8.36	0.08	Yes
The odours of the data samples from the final water samples (Euroa and Shepparton) are independent of the odour of the data sample from the jar test samples	182.41	<0.00001	No

Using the null hypotheses shown in Table 25, the panel demonstrated that they were able to distinguish between the final water and the settled water samples which was expected as the final waters had been disinfected using chlorine. However, the data from the panel shows that they were unable to distinguish between the different coagulants used or between the jar test

and the WTP samples. This suggests that the odour detected by the panel was independent of the coagulant used. Despite this, there were a number of points worth noting when looking at the expected values determined as part of the Chi squared calculations for H_0. There is a difference in odour between the jar tested samples and the settled water sample from the WTP (Appendix 5). These are:

- The number of earthy /musty odours detected decreased against the expected value when using ACH;
- The number of no odour detections was greater than the expected value when using ACH;
- The ferric sulphate samples had a greater number of other odour detects than the expected value, and there were fewer earthy /musty odours detected than the expected value;
- The earthy /musty odours detected for the WTP samples were greater than the expected values;
- The earthy /musty odours for the aluminium sulphate sample were equal to the expected value.

These results align with the DOC removal rates shown in Table 16 indicating that the use of chemical coagulants specific for organics removal may improve the odour of the final water at Euroa WTP.

Despite the variability of DOC removal seen in the samples treated with ACH, these samples were shown to lead to fewer odour detections. This was unexpected, however the greater removal of the fluorescent humic and fulvic acid-like substances likely assisted in the increased detections of no odours.

The ferric sulphate jar tested samples showed a change in odours from earthy /musty in the raw water to “other” odours being detected. This is in spite of the higher DOC removal rates seen, therefore the chemical coagulant may have some influence on the odours detected despite the null hypothesis suggesting otherwise. However, there was still a lesser number of earthy /musty odours detected by the panel than the aluminium sulphate treated samples which suggests that there is an improvement in odours detected.

5.3 Summary

Optimisation of aluminium sulphate coagulation showed very little advantage over the current WTP operation. The DOC and UVA removal rates were similar with little change seen in the fluorescent humic and fulvic acid – like substances. The odours were similar to the WTP with earthy /musty odours still being the main odour detected. The LC-OCDs showed a different

pattern from the WTP sample, with the WTP sample showing a large reduction in humic substances whereas the chromatograms for the aluminium sulphate sample showed a significant concentration of residual humics.

The sludge density from the ACH coagulation is considered to be too low to work suitably in the existing clarifier. However, in all other aspects ACH is considered a good option as the data indicates that its use at the WTP would reduce odours as well as decrease the DOC concentrations and reducing the formation of THMs. Through the use of the EEM spectra the content of fluorescent humic and fulvic acid - like substances was shown to be reduced.

Coagulation with ferric sulphate was similar to that with ACH with respect to DOC and UVA removal. The sludge volumes indicated that the sludge was heavy and would work very well with the existing clarifier. The odour results showed that there was a change in odour, however the panel were not clear if this was positive or negative in comparison to the existing odours resulting from the WTP treatment process. Similar to the ACH the EEMs demonstrated a reduction in fluorescent humic and fulvic acid- like substances.

Based on the overall improvement in odour, and the reduction in organic matter, both ACH and ferric sulphate are considered superior to aluminium sulphate for coagulation. With respect to the operation of the WTP the use of ferric sulphate is considered to be the most appropriate option.

Before any final recommendations could be made a TBL assessment was conducted on the various options for improvement of taste and odour issues at Euroa. The outcomes of these are described in the next chapter.

6 Triple bottom line assessment and outcomes

A triple bottom line assessment was conducted to understand the most appropriate option with regard to the findings from Chapters 4 and 5. GVW utilises a triple bottom line assessment in decision making processes to understand the balance between financial, social and environmental issues. In some cases a fourth component is assessed which looks at the technical requirements and the impact on the operational team responsible for the asset. In this study this aspect has been incorporated into the social assessment.

The financial assessment took into consideration the chemical costs, landfill disposal costs and the potential impact on the existing infrastructure program.

The environmental assessment took into consideration the impacts on landfill through the generation of sludge, as well as the potential carbon emissions of heavy vehicles based on the volumes of coagulation chemicals required to be delivered and the volumes of sludge being disposed of to landfill.

The social assessment took into consideration how improved odour of the treated water will impact on the community and GVW staff. The technical assessment included in the overall social assessment takes into consideration how the site operator will be impacted.

Details of the TBL assessment can be found in Appendix 6.

6.1 Economic assessment

6.1.1 Cost of treatment at the WTP

The monthly chemical cost required to produce water was determined using 12 months' worth of GVW process data from February 2014 to January 2015. Chemical dose rates were sourced at hourly intervals and the volume of water produced was determined as a total for the month. Based on the findings in Chapter 5 that showed an increase in the humic acid - like substances following rainfall, the monthly rainfall was reviewed in conjunction with the costs.

Figure 34 details the chemical cost per ML of water produced per month, including the individual chemical cost per ML ($/ML). Although the polymer (Flopam 4190 PWG) is utilised on site as a coagulation aid, the overall contribution to the chemical costs is negligible (~$0.001 /ML) due to the very low volumes used. Therefore, this cost has not been included. The cost of chemicals per ML of water produced was plotted against corresponding monthly rainfall for the area.

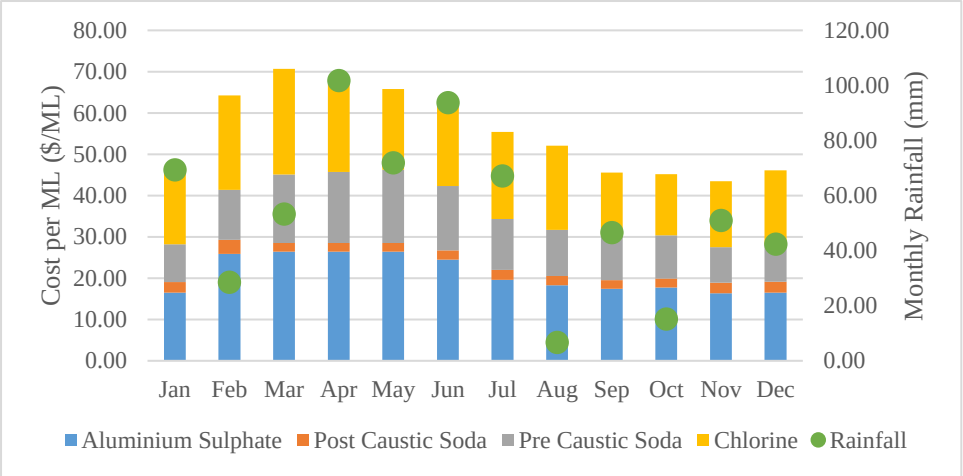


Figure 34: Chemical Cost per ML of Water Produced in 2014 including the Monthly Rainfall

Figure 34 shows that coagulation (aluminium sulphate and pre-caustic) accounts for the bulk of the chemical cost at Euroa WTP ($14,750 per annum for aluminium sulphate and $8,600 per annum for pH correction). Although the chemical cost at Euroa was not high across the year in comparison to other GVW sites, the overall cost per ML of water produced for the WTP was high in comparison to other GVW sites. This was mostly due to the raw water quality, especially the NOM content, which results in a higher chemical coagulant requirement than other sites.

The high coagulation cost ($/ML) was likely attributable to the operator practice of overdosing to meet changing water quality. Figure 34 shows the rising use of aluminium sulphate between February and June. The rainfall in February and March was lower compared to other months, however the rainfall between April and June was higher than the other months. Although there appears to be some trend associating rainfall and the changing chemical cost, there is enough inconsistency to suggest there is no direct relationship between the monthly rainfall and chemical dose rates. There is potential that daily rainfall would have a greater impact on the overall chemical costs and could be investigated further.

The data in Figure 34 shows that the changes in pH correction (both pre -coagulation and post -filtration dosing) tend to be in line with the aluminium sulphate dose rate. This is expected as the addition of aluminium sulphate will decrease the pH to below the effective pH range for coagulation. The chlorine dose rate also appears to increase slightly with the increased aluminium dose rate. This is likely attributable to higher levels of NOM in the raw water creating a need to increase the aluminium sulphate dose rate for coagulation. As shown in Chapter 5, where there is a higher concentration of DOC in the raw water it is likely to also have a higher residual DOC in the coagulated and filtered water increasing the chlorine demand.

6.1.2 Potential cost of treatment based on jar test results

The average cost of treatment was determined for each chemical and compared to the WTP cost (Figure 35). These data include the cost of post chemical dosing requirements of caustic soda and chlorine.

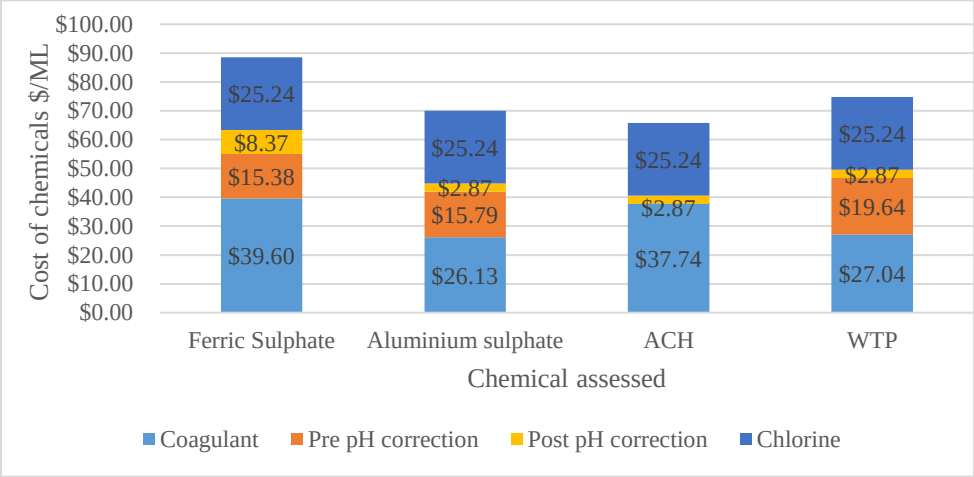


Figure 35: The average chemical cost determined based on jar tests and the WTP dose rates

The data presented in Figure 35 shows the average total cost of treatment per ML of water produced with the mean for each chemical. These data correspond with the findings reported in Chapter 5.2.1, showing that the average total cost per ML of water produced for aluminium sulphate (N = 11, Std Dev = $5.22) is slightly less than the average WTP cost (N = 11, Std Dev = $8.77). This supports the current site practices of overdosing to meet changing water quality requirements. The post chemical dosing is the same for the WTP and the aluminium sulphate jar test based on the final water quality.

ACH was determined as having the lowest average coagulant cost (N=12, Std Dev = $4.04), which is due to not requiring pH correction for coagulation. The post chemical dosing was shown to be similar to that for the WTP. The use of ACH provides good DOC removal and odour testing results showed it to be cost effective. This does not include the slight increase in polymer dosing costs (~$7.10 p.a.) or the potential costs of bentonite (~$284 p.a.) as these are not considered as consequential in comparison to other chemical costs, and changing to ACH, even when using bentonite, would still provide a financial benefit to GVW. The cost of these are low in comparison to the other chemicals as they have low purchase prices and the volumes used are small.

The use of ferric sulphate (N = 9, Std dev = $3.06) was shown to have a higher average cost than aluminium sulphate. However the odours were determined to result in less earthy /musty odours than using aluminium sulphate. As coagulation was undertaken at a lower pH (~pH 5)

than aluminium sulphate consideration was given to the impact of post filtration pH correction. The required dose to raise the pH from 5 to 6.5 was shown to be 17 mg/L of caustic soda which is approx. $8.37 ML.

The annual cost of treatment was evaluated based on 710 ML of finished water produced and summarised in Table 26. The estimated annual savings associated with each chemical coagulant are also given.

Table 26: Annual estimated chemical costs and associated savings

	Base case – current situation	Aluminium sulphate	Ferric sulphate	ACH
Annual cost	53,096	49,717	62,894	46,753
Estimated annual saving ($ /year)	0	3,380	-9,796	6,345

Based on the jar test results, regular checking and optimisation of the coagulant dose could reduce the annual costs by $3,380. This does not take into consideration any labour costs associated with the additional work load required for optimisation of the aluminium sulphate coagulation. When considering the use of ACH the potential addition of bentonite should be considered. The average cost of bentonite is $1 per kg. Based on the 10% w/v solution trialled, and the dose rates applied to increase the turbidity, at a maximum addition of 0.4 g/L (8 mL/2 L) the total additional cost per year would equate to approx. $284 which is not considered to be of consequence. Consideration was given to the cost associated with the disposal of the waste sludge produced by each chemical and was based on a total disposal cost of $175 /tonne of sludge produced, which includes the transport costs. The volume of wet sludge produced was based on the data shown in Table 22 and are approximate based on 710 ML of water produced. The volume of sludge used for the base case was 32,500 cm^3 of sludge produced per year at the WTP. The cost associated with landfill disposal are shown in Table 27.

Table 27: Annual estimated disposal costs with the volume of sludge produced

	Base case – current situation	Aluminium sulphate	Ferric sulphate	ACH
Sludge Cost ($ /year)	5,687	5,591	6,213	3,106
Estimated annual saving ($ /year)	0	90	- 526	2,581

The data in Table 27 shows that the cost associated with the volume of sludge produced through ACH coagulation is half that of the ferric sulphate sludge. The aluminium sulphate sludge cost is slightly lower than the base case which is expected given the lower coagulant dose rate seen through the optimisation.

The data shown in Table 26 and 27 were used to give a score based on descriptors shown in Table 4.

Table 28: Financial assessment based on the determined annual chemical costs

	Base case – current situation	Aluminium sulphate	Ferric sulphate	ACH
Score	0	1	-4	3

Therefore, financially ACH is the most attractive with respect to the chemical costs. Changing to ACH could reduce the chemical costs at Euroa by $6,345 per year based on 710 ML of finished water produced as well as decrease the costs associated with sending sludge to landfill. This includes the slight increase in polymer addition. The use of ferric sulphate provides GVW with the least attractive financial option based on chemical usage.

6.1.3 Impact on GVW infrastructure program

It was noted in Chapter 1 that GVW operates a $30 million per year Infrastructure program which also includes $800,000 p.a. for WTP optimisation works. Each item in this program requires justification and development of a business case. In the 2017/18 – 2022/23 period GVW has proposed $1.45 million in capital works.

The only project which would be impacted by the change of coagulants is a $1.1 million proposed upgrade to the existing sludge management facility. At present there are two x 960 m^3 sludge lagoons which allow the sludge to settle, with the supernatant being returned to the head of the WTP. The proposed upgrade will improve the solid - liquid separation process and subsequently water quality of the supernatant returned to the head of the works.

A change to ferric sulphate coagulation would potentially impact on the proposed works as the existing sludge settling ponds may be undersized which could require more frequent de-sludging. However, the density of the ferric sulphate sludge would make settlement in the ponds faster improving the supernatant quality returning to the head of the WTP.

The volume and density of the ACH sludge produced could potentially allow GVW to defer the $1.1 million in capital based on the sludge volumes produced. This is an attractive option as this would allow the business to reprioritise other works. Further consideration would need to be given to the ability to settle the low density sludge out in the existing system and this could negatively impact the quality of supernatant returning to the head of the WTP. The initial indications from trials using bentonite and the Flopam 4190 PWC suggest that the density of the floc could be increased, which would improve the compatibility of the ACH with the clarifier.

There would be no apparent change with respect to the sludge handling facilities between the optimisation of the aluminium sulphate coagulation against the current operation of the WTP.

The construction material of the 22000 L coagulant storage tank is high density polyethylene (HDPE) and considered to be compatible with all coagulants (Ineos Olefins and Polymers USA 2012). Therefore, the chemical storage and dosing facilities are considered to be suitable and compatible for all chemicals with no changes or increased storage requirements.

Therefore ferric sulphate and ACH were the only chemicals that would have an impact on the existing infrastructure program and the associated sludge removal costs. The financial assessment based on the impacts to the GVW infrastructure program is shown in Table 29.

Table 29: Financial scores based on the GVW infrastructure program

	Base case – current situation	**Aluminium sulphate**	**Ferric sulphate**	**ACH**
Score	0	0	0	2

The score for ACH was allocated because the use of ACH potentially allows $1.1 million to be deferred in the GVW infrastructure program, as well as a significantly reduced cost associated with the removal of the sludge produced. Hence the use of ACH provides the greatest benefit to GVW. The aluminium sulphate was rated the same as the base case as there was no foreseeable change in the requirement in the project. The ferric sulphate was also rated the same as the base case. This was because although the existing sludge lagoons may be undersized for the volume of sludge produced, the density of the sludge is such that it would

allow better solid - liquid separation in the system making the operation more efficient, this would also reduce the estimated cost of sludge removal.

6.1.4 Overall financial impacts

The total financial impact based on the use of different coagulation chemicals was determined. This was completed using the assessments of the operational costs and the impact on the infrastructure program and shown in Figure 36.

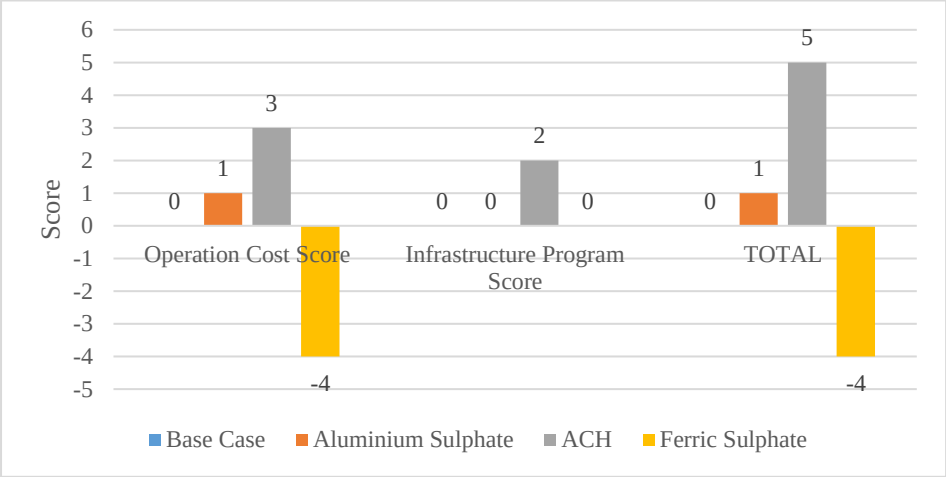


Figure 36: The combined financial assessment based on the impacts of each coagulant assessed

These results show that ACH coagulation is the most attractive option financially, followed by the optimisation of the use of aluminium sulphate. The use of ferric sulphate is the least attractive option financially.

6.2 Environmental impact assessment

At present, when the lagoons are at capacity they are decanted and the sludge left to dry. Once dried the sludge is dug out and the waste sludge disposed of to landfill. This is currently completed annually. The volume of sludge produced that would potentially end up as landfill was assessed as an environmental impact. Additionally, based on the volume of chemicals required to be delivered to site, the carbon emission resulting from the delivery tankers was assessed.

6.2.1 Sludge production and landfill impacts

The sludge volumes for each of the chemical coagulants were determined and are shown in Table 22. This was used as a basis to understand the impacts on the existing sludge lagoons. WTP sludge is considered to be a prescribed waste by the Victorian Environment Protection Authority (EPA) due to the aluminium content with very little potential for beneficial reuse (Environment Protection Authority of Victoria 2009) and in most cases, the waste sludge is

disposed of to landfill. Similarly, ferric based sludge is also considered as a prescribed waste by the EPA, and disposal to landfill is the most common method of removal.

The environmental impact associated with the sending waste sludge to landfill is shown in Table 30.

Table 30: Environmental impacts associated with landfill disposal

	Base Case – Current Situation	**Aluminium Sulphate**	**ACH**	**Ferric Sulphate**
Comment in comparison to base case	No change	Slightly less sludge produced.	A lot less sludge produced	More sludge produced
Score	0	1	3	-1

The volume of sludge produced by the ferric sulphate would be the most detrimental environmentally as there is more sludge produced than the base case. As previously mentioned, however, the density of the sludge is quite high which would improve the settlement within the lagoons, increasing the quality of water being returned to the head of the WTP.

The volume of sludge produced by ACH is significantly lower than for either the aluminium sulphate or ferric sulphate and so would reduce the volume of waste to be removed to landfill. As previously mentioned the density of the sludge produced by the ACH is low and therefore there may be some problems associated with the existing methods of the solid - liquid separation. This could potentially mean that there is some liquid wastage associated with the ACH sludge removal which would need to be managed appropriately.

The aluminium sulphate based sludge removal would be similar to the existing treatment process with very little change to the current operation of the sludge management facilities. However, as the volume of aluminium sulphate used was slightly less than the WTP, it is considered that there would be slightly less sludge produced annually if the coagulant was optimised.

This assessment showed that based on disposal of waste sludge to landfill, ACH coagulation was considered to be the most attractive option. Ferric sulphate coagulation was shown to be least attractive sludge, and optimised aluminium sulphate coagulation was considered as having a slight benefit over the base case.

6.2.2 Potential greenhouse gas emissions based on the coagulant change.

Changing coagulants would have environmental impacts upstream based on the production of the chemicals and the subsequent need to deliver chemicals to the site. The annual coagulant

and pH adjustment chemical volumes required have been determined based on 710 ML of water produced per annum.

The number of deliveries has been determined based on the current chemical delivery volume of 10000 L for both the coagulant and the caustic soda. The delivery volume is set at 10000 L because access to the site is not possible for larger tankers. As previously mentioned the existing chemical coagulant tanks are suitable for all of the chemical coagulants assessed. This means that the chemical delivery arrangements would remain the same. The number of deliveries and volumes of chemicals required per annum can be seen in Table 31.

Table 31: Annual chemical volume requirements and annual delivery requirements

	Base case – current situation	**Aluminium Sulphate**	**Ferric Sulphate**	**ACH**
Coagulant (L/ year)	66,619	64,361	47,115	19,849
Caustic soda (L/ year)	14,766	13,433	13,048	1,602
Deliveries required coagulant	7	7	5	2
Deliveries required caustic soda	2	2	2	1

The data shown in Table 31 indicates that there would need to be only two chemical deliveries required per year if GVW were to change to using ACH as a coagulant. This would significantly reduce the GHGs emitted associated with the deliveries.

The volume of aluminium sulphate used when optimised would be sufficiently similar to the current operation for the number of deliveries to be the same.

The use of ferric sulphate as a coagulant would have fewer delivery requirements compared to the current operation. Despite using less caustic soda as pH correction for coagulation, the increased extent of the post pH correction using caustic soda would increase the volume of caustic soda required to be similar to the current operation.

The CO_2 emitted for each delivery was determined using a figure of 600 g of CO_2 emitted per km driven with a full tanker load, and 500 g of CO_2 emitted per km driven with an empty tanker (Seo, et al., 2016). Chemical manufacture is completed on the outskirts of Western Melbourne and delivered approximately 180 km to Euroa. This figure was used to determine the CO_2 emissions assuming a full load to Euroa and an empty load returning to Melbourne. Based on the number of deliveries required in Table 31, the total volume of emissions for each coagulant was determined and is shown in Figure 37.

The same exercise was completed determining the GHGs emitted for the disposal of waste sludge for each coagulant. The sludge is disposed to the Euroa Resource Recovery Precinct which is situated 5.3 km from the WTP. The truck size was considered to hold 15,000 kg and the values of CO_2 emitted were based on Seo et al. (2016). These results are shown in Figure 37.

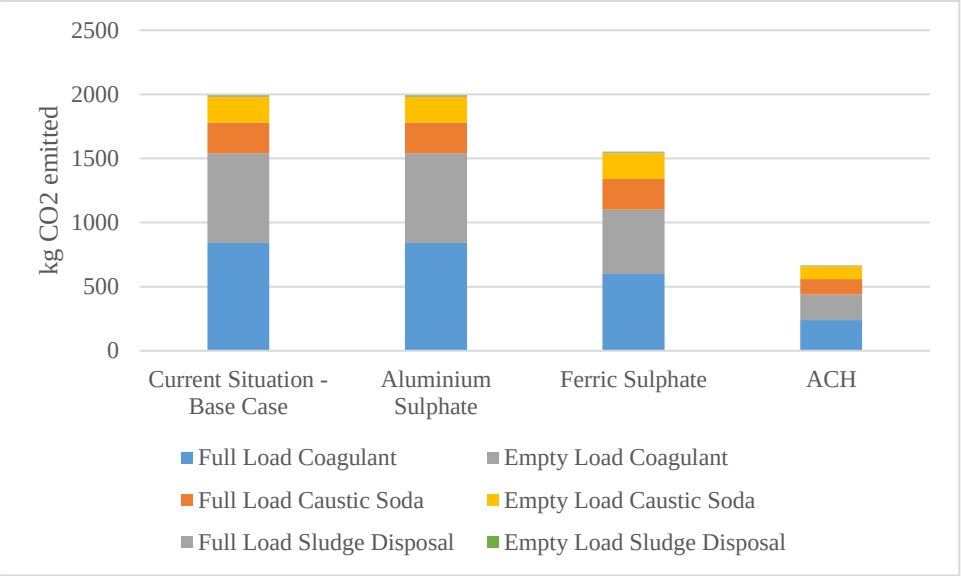


Figure 37: CO_2 emissions determined per year for each coagulant based on the delivery distance of 180 km and sludge disposal distance of 5.3 km each direction

The data shown in Figure 37 are an estimation only as there is limited information regarding heavy vehicle carbon emissions in Australia. The total carbon emissions from a vehicle is dependent upon many factors including vehicle weight, fuel quality and how the vehicle is being driven. The study by Seo et al. (2016) simulated these factors and gives a good basis for this estimation. The scores for each coagulant based on the carbon emissions determined are shown in Table 32.

Table 32: Scores Associated with the Environmental Assessment based on CO_2 Emissions

	Base case – current situation	Aluminium Sulphate	Ferric Sulphate	ACH
Score	0	0	2	4

These data demonstrate that the lower volumes of chemical required on site leads to fewer chemical deliveries being required. This ultimately results in a lower CO_2 emissions. Although the ferric sulphate produces more GHG emissions based on the sludge, this is offset by the fewer deliveries required for the coagulant. From this determination, ACH was the coagulant of choice with respect to reducing the carbon emissions.

6.2.3 Overall environmental assessment

The findings which review the environmental impact based on sludge waste being sent to landfill and the volume of carbon emissions have been combined into the overall environmental assessment (Figure 38).

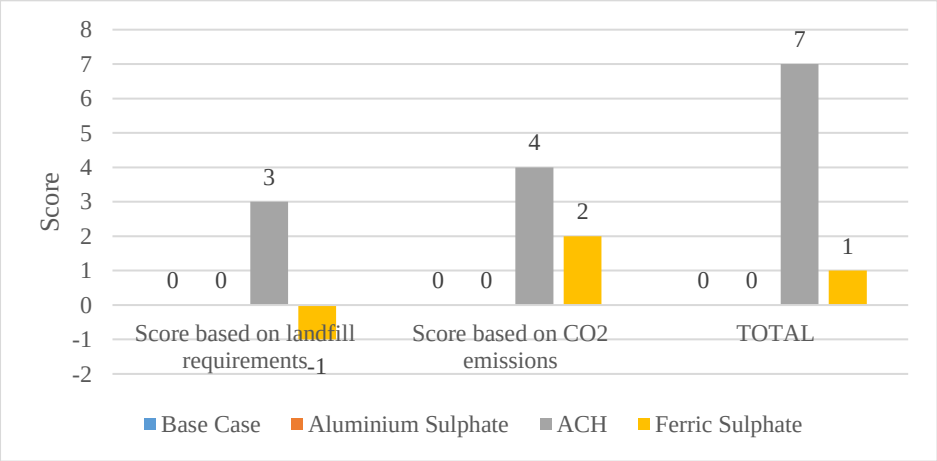


Figure 38: Overall findings from the environmental assessment

These results show that the most environmentally attractive option is the use of ACH. This relates to the fact that less coagulant is used requiring fewer chemical deliveries. Additionally, the volume of sludge produced would be significantly less potentially resulting in less waste being sent to landfill.

The use of ferric sulphate is slightly better environmentally than the base case or the use of optimised aluminium sulphate coagulation. This is mainly due to fewer deliveries required for the coagulant. The sludge volumes produced result in a slightly greater environmental impact than the base case or the aluminium sulphate, however this is slightly offset by the lower CO_2 emissions.

The use of aluminium sulphate as a coagulant was determined to have the same environmental impact as the base case.

6.3 Social impact assessment

6.3.1 Impact of improved odour on the community

As noted in Chapter 2, consumers' perceptions of drinking water safety are influenced by many factors. In particular the taste, odour, colour and turbidity of the water at their tap can influence how they perceive the safety of the water (Doria 2010). Poor taste and odour in drinking water, in particular chlorine odours, are cited as the key reason for consumers choosing alternative sources of drinking water such as bottled water (Puget et al. 2010). In Euroa, anecdotal evidence suggests that a number of customers on town water still maintain a

rainwater tank which is used primarily for drinking. When asked why, the general consensus was concern regarding the taste and odour of the water. This situation is not unusual with 24.3 % of residents in regional and rural Australia reporting that rainwater is their main drinking water source despite having potable water (Sinclair, Leder & Chapman 2005). The federal government's guidance on the use of rainwater tanks published in 2010 (EnHealth 2010) indicates that although rainwater tanks generally have a higher bacterial count (measured as Heterotrophic Plate Count) if they are well maintained and looked after they pose minimal risk to health (EnHealth 2010). However, within the same document it is stated that householders have a poor record of maintaining rainwater tanks. Therefore the long term health risk associated with drinking tank water was considered to be higher in comparison to reticulated water (EnHealth 2010).

The overall social impacts were determined in terms of the improvements in taste and odour based on the data shown in Section 5.2.4. For the purposes of this assessment it is anticipated that improved taste and odour would lead Euroa residents to use reticulated water in preference to tank water for drinking purposes.

From Section 5.2.4 it can be seen that the optimisation of the aluminium sulphate coagulation process had minimal impact on the treated water quality in comparison to that from the WTP. The associated odours remained as predominantly earthy /musty. Therefore, it is unlikely that the customers in Euroa would notice any difference between the optimised process and the current situation.

The use of ACH reduced the number of earthy /musty odours seen and increased the number of no odours detected by the panel. Based on this it is likely that the residents in Euroa would perceive an improvement in the overall quality of water and would tend to use reticulated water for drinking purposes.

Although the use of ferric sulphate tended to lead to fewer than expected earthy /musty odours, the panel detected an increase in other odours in the samples. Where other odours were detected the panel were unable to decide if it was a good or bad odour.

The community impact was then assessed by taking into consideration the reduction in exposure to health risks associated with drinking tank water. Table 33 shows the outcomes of the social assessment based on community impacts.

Table 33: Outcomes of the assessment concerning the impacts improved taste and odour would have on the community

	Base case – current situation	Aluminium Sulphate	Ferric Sulphate	ACH
Score	0	0	2	3

Therefore, based on the social assessment looking at the impacts to the community ACH is considered to give the greatest benefit due to the reduced number of earthy/musty odours detected and the increased number of no odours detected by the panel. The use of ferric sulphate as a coagulant was considered as the second best option due to the reduced number of earthy /musty odours detected, however the number of other odours detected could be unpleasant to some community members. It was considered that there was no difference considered between the current situation and the optimisation of the aluminium sulphate coagulation.

6.3.2 Impacts of improved odour on GVW employee satisfaction

GVW sees itself as a community-centric organisation with employees also being customers living in the community. This integration within the community leads to a lot of informal and word-of-mouth feedback, both positive and negative. GVW is a small company with only 208 staff members leading to a working environment where most people know each other. Where informal feedback from the community is received by a staff member it tends to be passed on to the employee that the feedback affects. Research into employee motivation shows that that recognition and praise improves self-esteem which in turn can improve employees' performance (Fulop & Linstead, 2009). Therefore by improving the taste and odour of drinking water from the Euroa WTP, knowing that it is a customers' measure of the level of service provided (Doria, 2010), then the overall work satisfaction of all employees may potentially improve. Brief informal discussion with the panel used in the taste and odour testing indicates that through the participation of this study, if the taste and odour of the water from Euroa WTP is improved, they would feel satisfaction in knowing that they were part of a project providing positive changes for the customers.

This theory is based on the positive feedback loop between increasing customer satisfaction and the in-turn satisfaction of the employees. This relationship has been studied in customer service industries such as hospitality and retail (Bulgarella, 2005). There has been little research into the impact of good customer satisfaction on employees involved in the provision of essential services.

The changes in odour and the potential for changes in perception seen by the community from Section 6.3.1 have been assessed with respect to the potential for feedback to occur. When

considering the optimisation of aluminium sulphate, the panel detected that the earthy /musty odours were similar to those for the WTP produced water. Therefore it is considered to be unlikely that the community would provide any feedback to GVW staff.

Coagulation using ACH showed a reduction in earthy /musty odours and an increased detection of no odours. With this change it is believed that the community could potentially perceive the improvements and provide any changed feedback to GVW staff members within the community.

The samples treated with ferric sulphate were shown to have a change in odour to a nondescript 'other' odour. Much of the literature on taste and odour perceptions indicate that people will make complaint if they move into a new area with different water quality or if the water quality is variable (Doria, 2010). Therefore it is likely that community members would notice the change and initially complain, however if the water quality remains constant these complaints may not occur in the future. With fewer complaints occurring in the longer term, it is likely the staff associated with the WTP will feel a greater sense of pride in their work and there will be a positive impact on their work satisfaction.

The scores based on a social assessment of the employee satisfaction based on informal feedback from the community is shown in Table 34.

Table 34: Social assessment based on employee satisfaction

	Base case – current situation	**Aluminium Sulphate**	**Ferric Sulphate**	**ACH**
Score	0	0	1	2

Based on this assessment ACH coagulation was considered to have the most beneficial outcome with respect to employee satisfaction. This was followed by the samples treated with ferric sulphate. The optimised aluminium sulphate system was shown to have no difference in comparison to the base case.

6.3.3 Technical assessment based on the potential changes in site operation and the impact of this on the WTP operator.

Without the contribution of the WTP operator there would be no improvements seen within the community. Therefore consideration of how a change in coagulant would impact on the operators needed to be undertaken. Items considered were:

- Jar testing requirements above and beyond the current GVW minimum requirements of monthly or where the water quality requires it;

- Interaction with hazardous chemicals during delivery;
- Operation and effectiveness of the coagulant dose within the clarifier; and,
- The operation of the supernatant return facilities, including the quality of water returned to the head of the WTP.

The ACH dose rates would decrease the interaction with coagulation and pH correction chemicals currently used on site. ACH is not considered as a dangerous material, and the use of ACH removes the pre-coagulation pH correction requirement. The low density floc seen in Section 5.2.5 makes the compatibility of the ACH treated raw water with the clarifier unknown. Additionally, this may impact on the solid-liquid separation in the sludge handling facilities decreasing the quality of water being returned to the head of the WTP. It is likely there would be an increased requirement to jar test, however this has not been quantified.

The reduced number of deliveries required for caustic soda when using ACH coagulation would reduce the exposure of the operator. Caustic soda is considered to be a hazardous material and has been known to cause severe skin burns. IT is considered to be more hazardous than either ferric sulphate or aluminium sulphate. Therefore by using ACH the health and safety risk of the operator would be decreased.

The use of ferric sulphate as a coagulant would not necessarily change the current situation with respect to interaction and contact with chemicals. There would be slightly fewer coagulant deliveries, which would be of benefit to the operator as ferric sulphate is considered to be a hazardous material due to the corrosivity and is considered to be more hazardous than aluminium sulphate. The high density floc resulting from coagulation using ferric sulphate is compatible with the current clarifier design leading to easier operation; similarly the use of ferric sulphate would lead to fewer jar tests meaning the current GVW requirements of monthly jar tests would be sufficient. The solid - liquid separation process in the sludge handling facilities would be compatible with the high density sludge leading to improved settling and therefore the quality of water returning to the head of the WTP would be improved.

The optimisation of aluminium sulphate coagulation would have limited impact on the operator in comparison to the base case with respect to site operation, chemical deliveries and management of the sludge handling facilities. However, in order to optimise the aluminium sulphate dose more jar testing would be required which would impact on the operator work load and time requirements. With the rapid changes seen in raw water quality at Euroa WTP, it is likely there would be a need to complete jar tests on a weekly basis whereas, the current GVW practice is monthly as a minimum.

Table 35 details the social assessment based on the impact on the WTP operator.

Table 35: Social assessment based on direct operator impact

	Base case – current situation	Aluminium Sulphate	Ferric Sulphate	ACH
Score	0	-1	3	-1

Therefore based on the findings in Table 35, the use of ferric sulphate as a coagulant was considered to be the preferred option with respect to the impacts on the operator. This consideration was predominantly made with regard to the ease of operation through the WTP. The use of ACH and the aluminium sulphate were considered to be the least preferred option based on the additional intervention required.

6.3.4 Outcomes of the social impact assessment

The combined results from looking at the impacts of improved odour on the community and GVW staff, as well as the impact the change in coagulant would have on the WTP operation and the subsequent impact on the WTP operator, are shown in Figure 39.

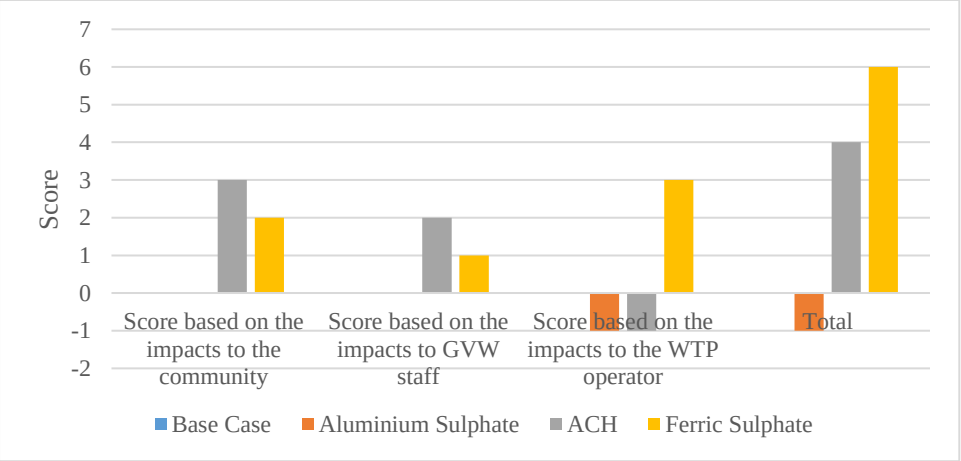


Figure 39: Summary of the findings from the social impact assessment

These results show that ferric sulphate as a coagulant is the most beneficial option, followed by the use of ACH. The optimisation of the aluminium sulphate was shown to be the least attractive option. This is predominantly based on the increased operator requirement for jar testing above and beyond the current GVW minimum requirements of monthly, or where the water quality requires it, while having no significant benefit to the community or other staff members based on odour improvements.

6.4 Triple bottom line assessment

Using the weightings from Table 4 the outcomes from the financial, social and environmental aspects were combined into a single output (Figure 40).

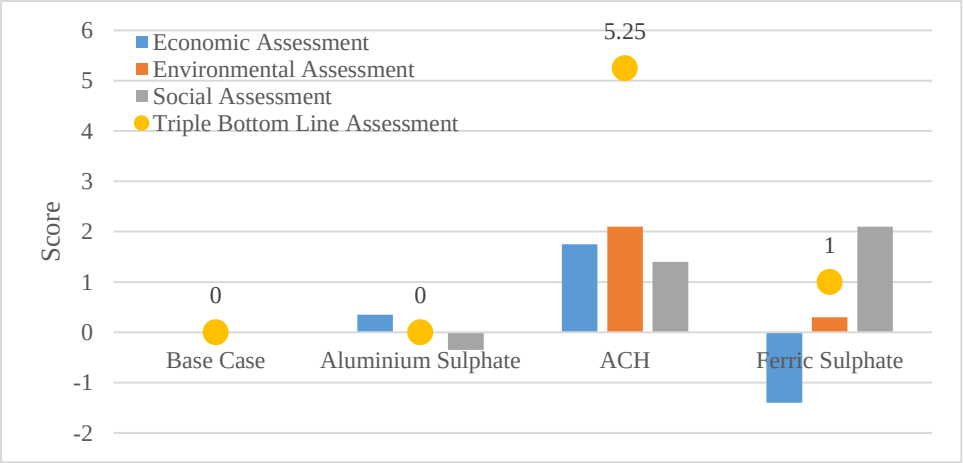


Figure 40: Summary of the outputs from the economic, environmental and social assessment

These results show that when taking all criteria into consideration, ACH is the most attractive option. The benefits of changing the coagulant to ACH occur for all TBL criteria. Financially, GVW would potentially save $6,345 per year in chemical costs as well as the potential to defer $1.1M of capital works. Environmentally, the volume of chemical used would be decreased, reducing the number of deliveries required and thus reducing the volume of CO_2 emissions. Additionally the use of ACH decreases the volume of sludge produced this reducing the amount of waste being sent to landfill. GVW has an Environmental Policy in place which commits GVW to reducing their environmental impact where possible. The use of ACH as a coagulant assists GVW with this commitment. Socially, the use of ACH would improve the odours in the treated water which would improve the community perceptions of their tap water which in turn could lead to more positive feedback to GVW staff and so increasing staff motivation and pride. The only negative associated with the use of ACH as a coagulant relates to the operation of the site and the low density floc that is formed. This will not only impact on the operation of the clarifier which may require greater intervention from the operator, but it is likely to impact on the solid-liquid separation in the sludge handling process, decreasing the quality of water returning to the head of the WTP, which again will impact on the operability of the site. However, further investigation into the use of a bentonite suspension may alleviate this issue.

Ferric sulphate was the second most attractive option based on the TBL assessment. Financially, the use of ferric sulphate as a coagulant would increase the annual chemical costs at Euroa WTP by approx. $9,796 per annum. Additionally, the current proposed upgrade to the sludge handling facilities may be too small for the volumes of sludge produced. However, the heavier floc produced would assist in the solid-liquid separation, improving the quality of water being returned to the head of the WTP. The volume of sludge produced also negatively

impacts on the environmental assessment as this would increase the amount of waste being sent to landfill and increases the volumes of associated GHGs. The negatives associated with this are slightly offset by the decreased number of chemical deliveries required as a result of the reduced volume of coagulant required each year. Socially, the use of ferric sulphate as a coagulant was the best option. This was mainly due to the operation of the site and the impact on the operator.

Optimisation of the aluminium sulphate coagulant system was shown to be less appealing than the base case. This was mostly due to no distinct changes in the odour seen by the panel which would afford no improvement in odours seen by the community. In addition to this the effort required by the operator to optimise the plant would increase the jar testing requirements at the site. There would be some financial benefit to optimisation, saving approx. $3,345 per annum. Environmentally there was no difference between the optimisation of the aluminium sulphate coagulation against the base case.

A sensitivity analysis was used to test the outcomes of the initial TBL assessment by increasing the weightings to favour the economic, social or environmental aspects. The weightings used in the sensitivity analysis are shown in Table 6A sensitivity analysis was used to test the outcomes of the initial TBL assessment by increasing the weightings to favour the economic, environmental or social aspects. The weightings used in the sensitivity analysis are shown in Table 6.

Table 6. The weightings were increased to 50% of the aspect being favoured. The outcomes of the sensitivity analysis are shown in Figure 41.

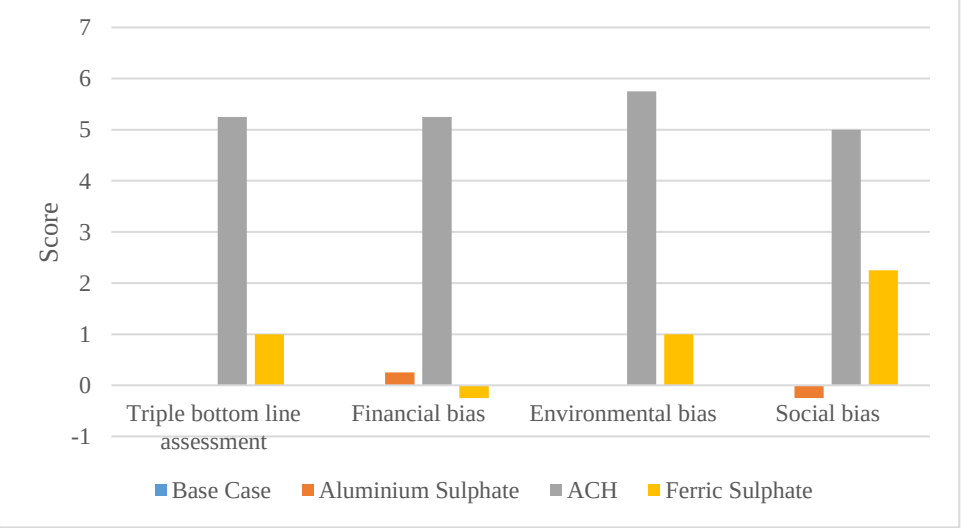


Figure 41: Outcomes from the sensitivity analysis

The use of the sensitivity analysis further supports the original findings from the triple bottom line assessment showing that for Euroa WTP, ACH coagulation is the most attractive option financially, socially and environmentally.

7 Conclusions and recommendations of further work

This chapter provides a summary of the case study reflecting on the research questions posed in Chapter 1. Further to this, recommendations of further work required resulting from this research were made.

7.1 Conclusions

Through the use of a taste and odour panel the predominant odours of the water treated by Euroa WTP were determined as earthy /musty and chlorinous, whereas no specific tastes were detected.

The presence of earthy /musty odours in the reticulation system suggested that geosmin and MIB may be present however, there were no detections above the odour detection limit disproving the theory that these were responsible for the earthy/musty odours. The free chlorine residual seen at the WTP was consistently above the aesthetic limit for chlorine and was considered the cause of the chlorine odours detected.

Correlation of water quality parameters to odours detected by the panel showed that SUVA provides an indication where an earthy musty or chlorinous odour may occur. DOC and UVA were shown to have a non-linear relationship with the odours. There appeared to be an optimum point where fewer odours were detected, this was at UVA = 0.48 /cm and DOC = 12 mg/L. DOC is currently determined through SGS Laboratories, whereas UVA or UVT can be measured on site using a bench top analyser. In order to give the operator an understanding of the characteristics of the NOM present in the water, a linear relationship between the UVA and DOC concentration was developed. This was determined to be:

$$DOC = 13.4\ UVA + 1.2$$

As expected, the free chlorine residual related back to the chlorinous odours detected. However, it was stronger at the point of disinfection than on the outlet of the storage. There was also a linear relationship between the earthy /musty odours detected and the free chlorine residual.

Therefore, the use of SUVA, DOC, UVA and free chlorine are useful tools for the operator at Euroa WTP to determine where a taste and odour issue may occur and so enable the treatment process to be optimised for organics removal.

In order to assist the operator with the optimisation, an equation to determine the aluminium sulphate dose was developed using turbidity and UVT. This equation can be used under normal operational conditions as a guide for the WTP Operator to check their coagulant dose

rate. This equation was not designed to eliminate the need for regular jar testing, or for use during periods of changing raw water quality. This equation was determined as:

$$\text{Aluminium sulphate dose rate (mg/L)} = 141.4 - 0.86\text{UVT} - 0.71\text{Turbidity}$$

However, optimisation of the aluminium sulphate coagulation for DOC removal showed no change in the odours detected with earthy /musty being the predominant odours detected by the panel. In addition to this the DOC removal rates through jar testing showed to be slightly less than the WTP (55 % and 57 % respectively). Therefore, it is unlikely that the optimisation of the aluminium sulphate coagulation would provide any benefit with respect to the odours detected by the community.

Optimisation of the aluminium sulphate coagulation would result in a financial saving of $3,380 per year for chemicals and $90 per year for sludge disposal when compared to the current WTP operation. There would be no impact on the existing GVW infrastructure program resulting from the optimisation. There would be minimal environmental benefit to optimising the aluminium sulphate with no change in GHG emissions from chemical deliveries compared to the current operation. However, there would be a slight reduction in the amount of sludge sent to landfill through optimisation. With respect to the social benefits, there appeared to be no clear benefit to the community or staff members. The overall impact of optimising the aluminium sulphate coagulation on the operator would be greater than the current operation, as there would be an increased jar testing requirement.

The use of ferric sulphate was shown to have environmental and social benefits, however it was considered to be economically disadvantageous. Using ferric sulphate as a coagulant gave a higher DOC removal rate than the WTP (72 % and 57 %, respectively). The sludge produced using ferric sulphate was heavy and settled well, which indicates it would work well within the WTP potentially improving the performance of the clarifier. Following jar testing, the panel determined that there were more other odour detections than the expected value, however there were also fewer earthy /musty odours than the expected value indicating that the use of ferric sulphate would decrease the number of odours detected in the Euroa community.

Financially the use of ferric sulphate would increase the annual chemical costs by $9,796 and with the increased volume of sludge produced, there would be an annual increase in sludge disposal costs by $526. There is no ability to defer any current infrastructure projects. Environmentally, the use of ferric sulphate would reduce the GHG emissions associated with chemical deliveries in comparison to the WTP. Conversely, the volume of sludge being

disposed of to landfill would increase, however, as the density of the sludge produced is greater than the aluminium based sludge, the solid liquid separation in the sludge handling facility would be improved. Socially the reduced number of earthy /musty odours detected would see benefits to the community. This would in turn improve feedback provided to GVW staff improving morale and motivation. The use of ferric sulphate as a coagulant was considered to be the most advantageous to the WTP operator as it appears to be compatible with the existing clarifier and sludge handling facilities. This would potentially improve the process reducing the interaction required by the operator.

The use of ACH as a coagulant was shown to have economic, environmental and social benefits. Using ACH as a coagulant gave a slightly higher DOC removal rate than the WTP (59 % and 57%, respectively). However, the sludge produced using ACH was of low density with floc remaining in suspension following settling. Initial experiments showed that the use of a polymer and a bentonite suspension to increase turbidity would improve the sludge density and settlement. Following jar testing, the panel determined that there were more no odour detections than the expected value, indicating that the use of ACH would decrease the number of odours detected in the Euroa community.

Financially the use of ACH would decrease the annual chemical costs by $6,345 and with the reduced volume of sludge produced, there would be an annual saving of $2,581 based on the reduced sludge disposal requirements. In addition to this, the reduced sludge volumes could result in the deferral of a $1.1 million upgrade to the existing sludge handling facilities. Environmentally, the use of ACH would reduce the GHG emissions associated with chemical deliveries and the volume of sludge being disposed of to landfill would be reduced. Socially the improved odours would see benefits to the community which in turn would improve feedback being given to GVW staff improving morale and motivation. However, the use of ACH may cause some operational issues at the WTP based on the low density sludge. As previously mentioned the initial results from trials with bentonite are positive which would reduce this impact on the WTP operator.

Therefore, the use of alternative coagulants would improve the odours detected by the Euroa community, whilst providing social and environmental benefits to GVW. The use of ACH would provide a financial benefit whereas the use of ferric sulphate would increase the chemical and sludge disposal costs to the business.

GVW should reconsider the use of aluminium sulphate at Euroa WTP and investigate the use of ACH as a chemical coagulant further as ACH provides financial, social and environmental benefits.

7.2 Recommendations of further work

This case study was based on specific findings from Euroa WTP. The presence of NOM within the raw water was found to be the key source of taste and odours in the reticulation system. By using alternative coagulants, it was determined that the taste and odour of drinking water could be improved whilst improving social, environmental and economic aspects of the business. From this study some further research opportunities and further work were identified for GVW.

Firstly, as taste and odour is becoming an increased focus to GVW due to its customer centric direction, further emphasis should be placed on understanding the tastes and odours in the drinking water systems. This should also include the perceptions of the wider community of the taste and odour of their drinking water. In addition, the WTP operators could undertake further training to understand the importance of taste and odour in drinking water.

The case study showed that the operator's main focus was not primarily on organics removal, however there was an awareness of the impact of organics on the treatment process. It is recommended that DOC analysers be installed on the raw water line at Euroa, and the use of SUVA be employed to identify where there may be taste and odours present in the reticulation system to enable adjustment of the chemical coagulation process accordingly. Further emphasis should be placed on the removal of NOM by GVW. Additional further correlations of clarified DOC concentrations against final water odours would be an interesting extension of this study.

The outcomes of this study suggest that ACH could be a more beneficial coagulant for Euroa WTP when social, environmental and economic parameters were considered, however there were some concerns regarding the compatibility with the existing WTP. Initial results showed that the use of Flopam 4190 PWC and bentonite improved the settling of the floc. It is recommended that the further investigation and lab trials into other polymers and bentonite addition should be completed prior to a plant trial. Further assessment could be undertaken to assess the impact of chlorination on the odour of the ACH coagulated water.

On a wider note it is suggested that further research be undertaken into the impact of different chemical coagulants that were not explored as part of this study on odours in the treated water. Consideration could be given to coagulants such as poly-ferric sulphate or more contemporary coagulants such as titanium or zirconium based salts.

Finally, it is recommended that the methodology and approach used in this research be extended to other GVW sites to understand if taste and odours issues in other areas can be predicted by a WTP operator based on simple water quality parameters.

References

Adams, C A, Muir, S & Hoque, Z 2014, 'Measurement of sustainability performance in the public sector', *Sustainability, Accounting, Management and Policy Journal* vol. 5, no.1, pp. 46-67.

Alvarez-Gaitan, J P, Peters, G M, Rowley, H V, Moore, S & Short, M 2013, 'A hybrid life cycle assessment of water treatment chemicals', *International Journal of Life Cycle Assessment* vol. 18, pp. 1291 - 1301.

Antonopoulou, M, Evgenidou, E, Lambropoulou, D & Konstantinou, I 2014, "A review on advanced oxidation processes for the removal of taste and odour compounds from aqueous media', *Water Research* vol. 53, pp. 215 - 234.

Ates, N, Kitis, M & Yetis, U 2007, 'Formation of chlorination by-products in waters with low SUVA - correlations with SUVA and differential UV spectroscopy', *Water Research* vol. 41, pp. 4139 - 4148.

Bae, B U, Kim Y I, Dugas, D W, Burlingame, G A, & Dietrich, A M 2002, "Demonstration of new sensory methods for drinking water taste and odour control." *Water Science and Technology* vol. 2, no. 5-6, pp. 241-247.

Bartels, J H M, Burlingame, G A & Suffet, I H 1986, 'Flavour profile analysis: taste and odour control of the future', *Journal (American Water Works Association)* vol. 78 pp. 50-55.

Benvenuti, J 2011, *Customer expectations - service standards in the next regulatory period and beyond*, Essential Services Commission, Melbourne, Vic.

Bond, T, Goslan, E H, Parsons, S A & Jefferson, B 2012, 'A critical review of trihalomethane and haloacetic acid formation from natural organic matter surrogates', *Environmental Technology Reviews* vol. 1 no.1 pp. 93-113.

Bruchet, A, Duguet J & Suffet, I 2004, 'Role of oxidants and disinfectants on the removal, masking and generation of tastes and odours', *Reviews in Environmental Science and Biotechnology* vol. 3 pp. 33-41.

Bulgarella, C C 2005, *Employee satisfaction & customer satisfaction: Is there a relationship?*, Guide Star Research for Better Business Relationships, viewed 05 April 2017 <http://meetingmetrics.com/research_papers/whitepaper_cs_es_relationships.pdf>

Burlingame, G A, Dietrich, A M & Whelton, A J 2007, Understanding the basics of tap water' *Journal (American Water Works Association)* vol. 99 pp. 100-111.

Burlingame, G A, Doty, R L & Dietrich, A M 2017, 'Humans as sensors to evaluate drinking water taste and odour: a review', *Journal of the American Water Works Association* vol. 109 no. 11 pp. 13-24.

Chang, E E, Chiang, P C, Chao, S H & Lin Y L 2006, 'Relationship between chlorine consumption and chlorination by products formation for model compounds', *Chemosphere* vol. 64 pp. 1196-1203.

Chebat, J C, Davidow, M & Codjovi, I 2005, 'Silent voices: Why some dissatisfied consumers fail to complain', *Journal of Service Research* vol. 7 no. 4 pp. 328-342.

Chen, W, Westerhoff, P, Leenheer, J A, & Booksh, K 2003, 'Fluorescence excitation-emission matrix regional integration to quantify spectra for dissolved organic matter', *Environmental Science and Technology* vol. 37 no. 24 pp. 5701-5710.

Comrie, D, Evans, S, Gale, R & Kitney, P 2002, 'Taste and odour in drinking water: perception versus reality', *Water (Australia)* Vol. 29 pp. 20-24.

Deborde, M & van Gunten, U 2008 'Reactions of chlorine with inorganic and organic compounds during water treatment - kinetics and mechanisms: A critical review', *Water Research* vol. 42 pp. 13-51.

Dietrich, A, Hoehn, R,Dufresne, L, Buffin, L, Rashash, D & Parker, B 1995, 'Oxidation of odourous and nonodourous algal metabolites by permanganate, chlorine and chlorine dioxide', *Water Science and Technology* vol. 31 pp. 223 - 228.

Dietrich, A 2006, 'Aesthetic issues for drinking water', *Journal of Water and Health* vol. 4 pp. 11-16.

Doria, M D F 2006, 'Bottled water versus tap water: understanding consumers preferences', *Journal of Water and Health* vol. 4 no. 2 pp. 271-276.

Doria, M D F 2010, 'Factors influencing public perception of drinking water quality', *Water Policy* vol. 12 pp. 1-9.

Doria, M D F, Pidgeon, N & Hunter, P R 2009, 'Perceptions of drinking water quality and risk and its effect on behaviour: A cross national study', *Science of the Total Environment* vol. 407 no. 21 pp. 5455-5464.

Drikas, M 2003, 'Natural organic matter in drinking water: problems and solutions', *Natural Organic Matter in Drinking Water: Problems and Solutions,* Water Research Australia: Occasional Paper pp. 5-9.

Drikas, M, Dixon, M & Morran, J 2009, 'Removal of MIB and geosmin using granular activated carbon with and without MIEX pre-treatment', *Water Research* vol. 43 pp. 5151-5159.

Edzwald, J K & Kaminski, G S 2007, 'A simple method for water plant optimisation and operation of coagulation', American Water Works Association – Water Quality Technology Conference, Denver Colorado.

Edzwald, J K & Tobiason J E 1999, 'Enhanced coagulation: US requirements and a broader view', *Water Science and Technology* vol. 40 no. 9 pp. 63-70.

EnHealth 2010, '*Guidance on the use of rainwater tanks'* Commonwealth of Australia, Canberra ACT

Environment Protection Authority of Victoria 2009, '*Environment Protection (Industrial Waste Resource) Regulations',* Environment Protection Authority of Victoria, Melbourne VIC.

Essential Services Commission 2016, '*A New Model for Pricing Services in Victoria's Water Sector: Position Paper',* Essential Services Commission, Melbourne VIC

Essential Services Commission 2015 '*Generating Ideas on the Pricing Approach for Victoria's Water Sector',* Essential Services Commission, Melbourne VIC

Fabris, R, Chow, C & Drikas, M 2003, 'The Impact of Coagulant Type on NOM removal' *Organic Matter in Drinking Water: Problems and Solutions*, Water Research Australia: Occasional Paper pp. 17 - 25.

Falahee, M & Macrae, A W 1995, "Consumer appraisal of drinking water: Multidimensional scaling analysis." *Food Quality and Preference* vol. 6 pp. 327 - 332.

Fan, L, Harris, J L, Roddick, F A & Booker N A 2001, 'Influence of the characteristics of natural organic matter on the fouling of microfiltration membranes', *Water Research* vol. 35 no. 18 pp. 4455-4463.

Fowle, S E, Constantine, C E, Fone, D & McCloskey, B 1996, "An epidemiological study after a water contamination incident near Worcester, England in April 1994', *Journal of Epidemiology and Community Health* vol. 50 pp. 18 - 23.

Fulop, L & Linstead, S 2009, 'Motivation and meaning', in Linstead, S, Fulop, L & Lilley, S (eds) *Management and Organization,* Palgrave McMillan, London, U.K pp. 411-472.

Furness, M 2004, 'The Wem incident', in Gray, J & Thompson, K (eds) *Water Contamination Emergencies: Can We Cope?,* Royal Society of Chemistry, London, U.K pp. 11- 15.

Gallard, H & von Gunten, U 2002, 'Chlorination of natural organic matter: Kinetics of chlorination and THM formation', *Water Research* vol. 36 pp. 65-74.

Gang, D, Clevenger, T E & Banerji S K 2003, 'Relationship of chlorine decay and THMs formation to NOM size', *Journal of Hazardous Materials* vol. A96 pp. 1-12.

Garcia-Villanova, R.J, Garcia, C, Gomez, J A, Garvia, M P & Arduany R 1997, 'Formation, evolution and modeling of trihalomethanes in the drinking water of a town: I. At the municipal treatment utilities." *Water Research* vol. 31 no. 6 pp. 1299 - 1308.

Ghernaout, D & Ghernaout, B 2012, 'Sweep flocculation as a second form of charge neutralisation - A review', *Desalination and Water Treatment* vol. 44 pp. 15-28.

Huber, S A, Balz A, Abert M & Pronk W 2011, 'Characterisation of aquatic humic and non-humic matter with size exclusion chromatography - organic carbon detection - organic nitrogen detection (LC-OCD-OND)', *Water Research* vol. 45 pp. 879-885.

Ineos Olefins and Polymers USA 2012, '*HDPE Chemical Resisance Guide',* USA: Ineos Olefins and Polymers.

Infrastructure Partnerships Australia 2015, '*Doing the Important, as Well as the Urgent',* Water Services Association of Australia Melbourne VIC.

Jardine, C G, Gibson, N & Hrudey, S E. 1999, 'Detection of odour and health risk perceptions of drinking water', *Water Science and Technology* vol 40 no. 6 pp. 91-98.

Jarvis, P, Jefferson, B & Parsons, S A 2004, 'Characterising natural organic matter flocs', *Water Science and Technology: Water Supply* vol. 4 no. 4 pp. 79-87.

Jarvis, P, Sharp E, Pidou, M, Molinder, R, Parsons, S A & Jefferson B 2012, 'Comparison of coagulation performance and floc properties using a novel zirconium coagulant against traditional ferric and alum coagulants', *Water Research* vol. 46 no.13 pp. 4179-4187.

Jung, S.W, Baek, K H & Yu M U 2004, 'Treatment of taste and odour material by oxidation and adsorption', *Water Science and Technology* vol. 49 no. 9 pp. 289-295.

Juttner, F & Watson, S B 2007, 'Biochemical and ecological control of geosmin and 2-methylisoborneol in source waters', *Applied and Environmental Microbiology* vol. 73 no. 14 pp. 4395 - 4406.

Karney, B W 2007, 'Life cycle energy use and greehouse gas emissions inventory for water treatment systems', *Journal of Infrastructure Systems* vol. 13 no. 4 pp. 261-270.

Korotta-Gamage, S & Sathasivan, A 2017, 'A review: Potential and challenges of biologically activated carbon to remove natural organic matter in drinking water purification process', *Chemosphere* vol. 167 pp. 120-135.

Lai, E, Lundie, S & Ashbolt N J 2008, 'Review of multicriteria decision aid for integrated sustainability assessment of urban water systems', *Urban Water Journal* vol. 5 no. 4 pp. 315 - 327.

Liato, V & Aider M 2017, 'Geosmin as a source of the earthy-musty smell in fruits, vegetables and water: Origins, impact on foods and water, and review of the removing techniques', *Chemosphere* vol. 181 pp. 9-18.

Lin, S D 1977, '*Taste and odours in water supplies - A review',* State of Illinois, Department of Registration and Education.

Littelchild, S & Mountain, B 2015, Customer engagement methodologies in water price setting: Experience in England and Wales and Scotland, and possible application to Victoria', Essential Service Commission, Melbourne VIC.

Liu, T, Chem Z L, Yu, W & You, S 2011, 'Characterisation of organic membrane foulants in a submerged membrane bioreactor with pre-ozonation using three-dimensional excitation-emission matrix spectroscopy', *Water Research* vol. 45 pp. 2111-2121.

Lundie, S, Peters, G, Ashbold, N J, Lai, E & Livingston D 2006, 'A sustainability framework for the Australian water industry', *Water: Journal of The Australian Water Assoication* , vol. November pp. 54 - 59.

MacCarthy, P 2001, 'The principles of humic substances: An introduciton to the first principle', in Ghabbour, E A (Ed.), *Humic Substances Structure, Models and Functions*, Cambridge, UK, Royal Society of Chemistry (Great Britain), pp. 19 - 30

Marlow, D R, Beale, D J & Burn, S 2010, 'A pathway to a more sustainable water sector', *Water Science and Technology* vol. 61 no. 5 pp. 1245-1255.

Marques, R C, da Crux, N F & Pires, J 2015, 'measuring the sustainability of urban water services', *Environment Science and Policy* vol. 54 pp. 142-151.

Matilainen, A, Gjessing, E T, Lahtinen, T, Hed, L, Bhatnagar, A & Sillanpaa, M 2011, 'An overview of the methods used in the characterisation of natural organic matter in relation to drinking water treatment', *Chemosphere* vol. 83 pp. 1431-1422.

Matilainen, A, Vepsalainen, M & Sillanpaa, M 2010, 'Natural organic matter removal by coagulation during drinking water treatment', *Advances in Colloid and Interface Science* vol. 159 pp. 189-197.

McDonald, S, Lethorn, A Loi, C, Dreissen, H, Joll, C A & Heitz, A 2009, '*Causes and prevention of chlorinous off flavours in potable water',* Water Quality Research Australia, Perth, WA.

McDonald, S, Joll C A, Lethorn, A, Loi, C & Heitz, A 2013, 'Drinking water: The problem of chlorinous odours', *Journal of Water Supply: Research and Technology - Aqua* vol. 62 pp. 86-96.

McGuire, M J 1995, 'Off-flavour as the consumer's measure of drinking water safety', *Water Science and Technology* vol. 31 no.11 pp. 1-8.

Mishra, B, Gupta, S & Sinha A 2013, 'significance and importance of water quality parameters for predictive modeling approach of disinfection byproduct (DBP) in drinking water - A review', Global Science and Technology Forum, Singapore.

Murray, B & Mosse, P 2015, '*Practical Guide to the Optimisation of Chemical Dosing, Coagulation, Flocculation and Clarification',* 2nd edn. Water Industry Operators Association of Australia, Shepparton VIC.

National Health and Medical Research Council 2011, '*Australian Drinking Water Guidelines',* National Health and Medical Research Council, Canberra ACT.

Ortenberg, E & Telsch, B 2003, 'Taste and Odour Problems in Potable Water', in Mara, D & Horan, N (eds) *Handbook of Water and Wastewater Microbiology,* Academic Press, London UK, pp. 777-794.

Piriou, P, Mackey, E, Suffet, I H & Bruchet A 2004, 'Chlorinous flavour perception in drinking water', *Water Science and Technology* vol. 49 pp. 321-328.

Proulx, F, Rodriguez, M, Serodes, J & Miranda, L 2010, 'Factors influencing public perception and the use of municipal tap water', *Water Science and Technology: Water Supply* vol. 10 pp. 472-485.

Puget, S, Beno, N, Chabanet C, Guichard, E & Thomas-Danguin, T 2010, 'Tap water consumers differ from non-consumers in chlorine flavour acceptability but not sensitivity', *Water Research vol.* 44 pp. 956 - 964.

Roccaro, P, Vagliasindi, F & Korshin, G V 2009, 'Changes in NOM fluorescence caused by chlorination and their association with disinfection by-products formation', *Environmental Science and Technology* vol. 43 no. 3 pp. 724 - 729 .

Rodrigo, S, Leder, K & Sinclair, M 2009, '*Quality of stored rainwater used for drinking in metropolitan South Australia',* Water Quality Research Australia, Adelaide SA.

Rutlidge, H, Anderson, M S, Baker, A, Chinu, K J, Cuthbert, M O, Jex, C N, Marjo, C E, Markowska, M & Rau, G C 2015, 'Organic characterisaion of cave drip water by LC - OCD and fluorescence analysis', *Geochimica et Cosmochimica Acta* vol. 166 pp. 15-28.

Seo, J, Park, J, Oh, Y & Park, S 2016, 'Estimation of total transport CO_2 emissions generated by medium and heavy duty vehicles in a sector of Korea', *Energies,* vol. 9, no. 8, viewed 03 April 2017, < http://www.mdpi.com/1996-1073/9/8/638/htm>.

Sinclair, M I, Leder, K & Chapman, H 2005, '*Public health aspects of rain water tanks in urban Australia',* Co-operative Research Centre for Water Quality and Treatment Salisbury, SA.

Slaper, T F & Hall, T J 2011, 'The triple bottom line: What is it and how does it work', *Indiana Business Review* vol. Spring pp. 4-8.

Soh, Y C, Roddick, F & van Leeuwen, J 2008, 'The impact of alum coagulation on the character, biodegradability and disinfection by-product formation potential of reservoir natural organic matter fractions', *Water Science and Technology* vol. 58 no. 6 pp. 1173 - 1179.

Srinivasan, R, & Sorial G A 2011, 'Treatment of taste and odour causing compounds 2-methylisoborneol and geosmin in drinking water: A critical review', *Journal of Environmental Sciences* vo. 23 no. 1pp. 1-13.

Suffet, I, Mallevialle, J & Kawczynski, E 1995, '*Advances in taste and odour treatment and control',* American Water Works Association Research Foundation, Denver CO.

Suffet, I, Khiari, D & Bruchet, A 1999, 'The drinking water taste and odour wheel for the millenium: Beyond geosmin and 2-methylisoborneol', *Water Science and Technology,* vol. 40, no. 6, pp. 1-13.

Tan, Y, Kilduff, J, Kitis, M & Karanfil, T 2005, 'Dissolved organic matter removal and disinfection byproduct formation control using ion exhange', *Desalination, vol.* 176, pp. 189 - 200.

The Water Services Regulatory Authority 2011, 'Involving Customers in Price Setting - Ofwat's Customer Engagement Policy Statement', OFWAT, London UK.

Tondelier, C, Benanou, D, Thouvenot, T & Genin, A 2008, 'Novel on-tap passive sampling for odour compounds in drinking water', *Water Science and Technology: Water Supply,* vol. 8, no.2, pp. 197-205.

Twort, A, Ratnayaka, D & Brandt, M 2000, '*Water Supply',* 5th edn, IWA Publishing & Butterworth- Heinemann, London, UK.

Umar, M, Roddick, F & Fan, L 2014, "Effect of coagulation on treatment of municipal wastewater reverse osmosis concentrate by UVC/H_2O_2', *Journal of Hazardous Materials* vol. 266, pp. 10-18.

Umar, M, Roddick, F & Fan, L 2016, 'Comparison of coagulation efficiency of aluminium and ferric based coagulants as pre-treatment for UVC/H_2O_2 treatment of wastewater RO concentrate', *Chemical Engineering Journal* vol. 284, pp. 841 - 849.

Water Industry Commission of Scotland 2015, '*The customer forum for water in Scotland: Legacy report',* Water Industry Commission of Scotland. Glasgow, Scotland.

Water Research Foundation 2014, '*Advancing the science of water: WRF and research on taste and odor in drinking water',* viewed 5 April 2014, <www.waterrf.org/resources/StateoftheScience Reports/TasteandOdorResearch.pdf>.

Watson, S 2004, 'Aquatic taste and odour: A primary signal of drinking-water integrity', *Journal of Toxicology and Environmental Health. Part A: Current Issues* vol. 67, pp. 1779-1795.

Wnorowski, A 1992, 'Tastes and odours in the aquatic environment, a review', *Water,* vol.18, pp. 203-214.

Zamyadi, A, Henderson, R, Stuetz, R Hofman, R, Ho, L & Newcombe, G 2015, 'Fate of geosmin and 2-methylisoborneol in full scale water treatment plants', *Water Research,* vol. 83, pp. 171-183.

Zamyadi, A, Sawade, E, Ho, L, Newcombe, G & Hofman, R 2015, 'Impact of UV-H_2O_2 advanced oxidation and aging processes on GAC capacity for the removal of cyanobacterial taste and odour compounds', *Environmental Health Insights,* vol. 9, no. S3, pp. 1-10.

8 Appendices

Appendix 1. Ethics Approval

RMIT UNIVERSITY

RMIT University

Science Engineering and Health

College Human Ethics Advisory Network (CHEAN)

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27th September 2013

Felicity Roddick
Building 7 Level 2, Room 7
School of Civil Environmental
& Chemical Engineering
RMIT University

Dear Felicity

BSEHAPP 38 – 13 RODDICK-CALLINGHAM Cost benefit analysis of taste and odour compound removal from drinking water

Thank you for submitting your amended application for review.

I am pleased to inform you that the CHEAN has approved your application for a period of **3 Years** from the date of this letter to **27th September 2016** and your research may now proceed.

The CHEAN would like to remind you that:

All data should be stored on University Network systems. These systems provide high levels of manageable security and data integrity, can provide secure remote access, are backed up on a regular basis and can provide Disaster Recover processes should a large scale incident occur. The use of portable devices such as CDs and memory sticks is valid for archiving; data transport where necessary and for some works in progress. The authoritative copy of all current data should reside on appropriate network systems; and the Principal Investigator is responsible for the retention and storage of the original data pertaining to the project for a minimum period of five years.

Annual reports are due during December for all research projects that have been approved by the College Human Ethics Advisory Network (CHEAN).

The necessary form can be found at: www.rmit.edu.au/staff/research/human-research-ethics

Yours faithfully,

Linda Jones
Chair, Science Engineering & Health
College Human Ethics Advisory Network

Cc Student Investigator/s: Tara Callingham s3418857 School of Civil Environmental & Chemical Engineering RMIT University
Other Investigator/s: Linhua Fan School of Civil Environmental & Chemical Engineering RMIT University

RMIT UNIVERSITY

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9th December 2014

Felicity Roddick
Building 7 Level 2, Room 7
School of Civil Environmental
& Chemical Engineering
RMIT University

Dear Felicity

BSEHAPP 38 – 13 RODDICK-CALLINGHAM Cost benefit analysis of taste and odour compound removal from drinking water

Thank you for addressing the issues raised by the CHEAN in reference to your recent amendment request for your Human Research Ethics project titled: *Cost benefit analysis of taste and odour compound removal from drinking water* which was originally approved by Science Engineering and Health CHEAN in September 2013 for a period of 3 Years.

I am pleased to inform you that the CHEAN has **approved** your amendment as outlined in your request and your research may now continue.

The CHEAN notes and thanks you for providing all documentation that incorporates these amendments. This documentation will be appended to your file for future reference and your research may now continue.

Please Note: Annual reports are due on the anniversary of the commencement date for all research projects that have been approved by the CHEAN. Ongoing approval is conditional upon the submission of annual reports failure to provide an annual report may result in Ethics approval being withdrawn.

Final reports are due within six months of the project expiring or as soon as possible after your research project has concluded.

Yours faithfully,

Dr Falk Scholer
Deputy Chair, Science Engineering & Health
College Human Ethics Advisory Network

Cc Student Investigator/s: Tara Callingham s3418857 School of Civil Environmental & Chemical Engineering RMIT University
Other Investigator/s: Linhua Fan School of Civil Environmental & Chemical Engineering RMIT University

College Human Ethics Advisory Network (CHEAN)
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Building 91, Level 2, City Campus/Building 215, Level 2, Bundoora West Campus

7 April 2017

Professor Felicity Roddick
School of Engineering
RMIT University

Dear Prof Roddick

BSEHAPP 38-13 Cost Benefit Analysis of Taste and Odour Removal in Drinking Water

Thank you for requesting an extension to your Human Research Ethics project titled: **Cost Benefit Analysis of Taste and Odour Removal in Drinking Water**, which was originally approved by Science Engineering and Health CHEAN in 2013 for a period of **3 years**.

I am pleased to inform you that the CHEAN has **approved** your extension as outlined in your request and the application is now approved until 5 August 2017.

The CHEAN notes and thanks you for providing all documentation that incorporates these amendments. This documentation will be appended to your file for future reference and your research may now continue.

The committee would like to remind you that:

All data should be stored on University Network systems. These systems provide high levels of manageable security and data integrity, can provide secure remote access, are backed up on a regular basis and can provide Disaster Recover processes should a large scale incident occur. The use of portable devices such as CDs and memory sticks is valid for archiving; data transport where necessary and for some works in progress; The authoritative copy of all current data should reside on appropriate network systems; and the Principal Investigator is responsible for the retention and storage of the original data pertaining to the project for a minimum period of five years.

Please Note: Annual reports are due on the anniversary of the commencement date for all research projects that have been approved by the CHEAN. Ongoing approval is conditional upon the submission of annual reports failure to provide an annual report may result in Ethics approval being withdrawn.

Final reports are due within six months of the project expiring or as soon as possible after your research project has concluded.

The annual/final reports forms can be found at:
www.rmit.edu.au/staff/research/human-research-ethics

Yours faithfully,

Associate Professor Barbara Polus
Chair, Science Engineering & Health
College Human Ethics Advisory Network

Cc Student Investigator/s: Tara Callingham s3418857 School of Engineering RMIT University
Other Investigator/s: Linhua Fan School of Engineering RMIT University

Appendix 2. Jar Test Results

Aluminium Sulphate Jar Tests

Date	UVA Raw (/cm)	DOC Raw (mg/L)	SUVA (L.m/mg)	Turbidity Raw (NTU)	Colour Raw (Hazen)	Jar Test Alum Dose (mg/L)	Jar Test Caustic Dose (mg/L)	Jar Test UVA (/cm)	Jar Test DOC (mg/L)	WTP Alum Dose (mg/L)	WTP Caustic Dose (mg/L)	WTP UVA (/cm)	Jar Test DOC (mg/L)
27/04/2015	0.48	8.45	5.67	4.49	104.00	115	33	0.06	4.04	75	22	0.07	4.62
5/05/2015	0.45	8.15	5.55	7.01	117.00	95	28	0.06	3.89	75	22	0.06	4.16
19/05/2015	0.63	9.80	6.38	15.29	177.00	104	30	0.07	4.53	90	28	0.06	4.16
26/05/2015	0.38	7.19	5.23	15.55	164.00	97.5	28	0.05	3.23	90	28	0.05	3.17
10/08/2015	0.59	9.52	6.2	11.2	172.00	120	35	0.05	3.58	90	22		
22/09/2015	0.57	9.33	6.09	8.88	144.00	115	33	0.07	4.40	115	37	0.07	4.28
9/10/2015	0.41	7.63	5.36	7.29	104.00	115	33	0.05	3.65	115	34	0.04	3.14
6/11/2015	0.48	8.43	5.65	4.46	133.00	105	30	0.06	3.84	95	27	0.28	
20/11/2015	0.43	7.89	5.44	7.15	100.00	105	30	0.10	5.77	115	37	0.11	6.06
22/08/2016	0.76	11.61	6.54	10.6	155.00	115	33	0.08	4.81	135	49.7	0.07	4.28
9/11/2016	0.36	9.26	3.92	13.6	116.00	115	33			135	50		
6/12/2016	0.68	9.10	7.45	5.48	100.00	130	38	0.10	3.70	135	49.7	0.08	3.50
11/01/2017	0.77	12.00	6.41	8.5	166.00	135	48	0.15	4.90	135	46.5	0.11	4.30
19/01/2017	0.82	11.00	7.49	15.1	191.00	125	36	0.12	4.50	135	46.5	0.11	4.60
31/01/2017	0.72	11.00	6.56	7.02	170.00	130	47	0.11	3.90	135	46.5	0.09	3.50
01/02/2017	0.53	7.7	6.98	4.54	122.00	115	33	0.18	3.00	135	46.5	0.07	3.00

Ferric Sulphate

Date	UVA Raw (/cm)	DOC Raw (mg/L)	SUVA (L.m/mg)	Turbidity Raw (NTU)	Colour Raw (Hazen)	Jar Test Ferric sulphate Dose (mg/L)	Jar Test Caustic Dose (mg/L)	Jar Test UVA (/cm)	Jar Test DOC (mg/L)	WTP Alum Dose (mg/L)	WTP Caustic Dose (mg/L)	WTP UVA (/cm)	Jar Test DOC (mg/L)
21/02/2015	0.48	11.6	6.54	10.6	155	120	64	0.06	2.95	135	50	0.07	3.21
6/05/2015	0.45	9.26	3.92	13.6	116	110	57	0.07	3.95	135	50	0.08	5.08
20/05/2015	0.63	9.10	7.45	5.48	100	100	34	0.17	2.30	135	50	0.08	3.50
25/11/2016	0.38	10.0	8.86	13.8	198	110	33	0.13	2.90	135	50	0.15	5.50
6/01/2017	0.59	12.0	6.41	8.50	166	110	33	0.07	2.80	135	47	0.11	4.30
11/01/2017	0.57	11.0	7.49	15.1	191	95	28	0.07	2.50	135	47	0.11	4.60
19/01/2017	0.41	11.0	6.56	7.02	170	100	30	0.07	2.30	135	47	0.09	3.50
31/01/2017	0.48	7.30	8.01	6.33	163	105	36	0.09	2.50	135	50	0.08	3.20
15/02/2017	0.43	7.70	6.98	4.54	122	100	30	0.15	2.40	135	47	0.11	3.00

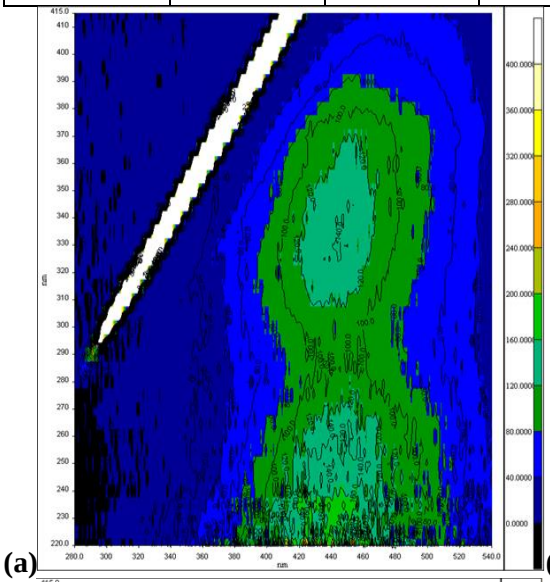
ACH

Date	UVA Raw (/cm)	DOC Raw (mg/L)	SUVA (L.m/mg)	Turbidity Raw (NTU)	Colour Raw (Hazen)	Jar Test ACH Dose (mg/L)	Jar Test UVA (/cm)	Jar Test DOC (mg/L)	WTP Alum Dose (mg/L)	WTP Caustic Dose (mg/L)	WTP UVA (/cm)	Jar Test DOC (mg/L)
6/11/2015	0.35	6.78	5.11	11.20	100	30	0.07	4.58	95	37	0.09	5.36
20/11/2015	0.43	7.89	5.44	8.88	133	35	0.09	5.31	115	37	0.11	6.06
2/12/2015	0.63	9.86	6.42	7.29	126	40	0.05	3.31	115	37	0.08	4.97
22/08/2016	0.48	8.45	5.67	4.46	116	35	0.05	3.45	115	35	0.06	3.99
7/09/2016	0.76	11.6	6.54	10.60	155	38	0.09	5.26	135	42	0.07	4.28
9/11/2016	0.36	9.26	3.92	13.60	116	35	0.10		135	50	0.08	5.08
6/12/2016	0.68	9.10	7.45	5.48	100	30	0.15	3.60	135	49	0.08	3.5
5/01/2017	0.89	10.0	8.86	13.90	198	45	0.10	3.40	135	50	0.15	5.5
11/01/2017	0.77	12.0	6.41	8.5	166	40	0.09	3.80	135	46	0.11	4.3
19/01/2017	0.82	11.0	7.49	15.1	191	42	0.10	3.40	135	46	0.11	4.6
31/01/2017	0.72	11.0	6.56	7.02	170	42	0.24	3.10	135	46	0.09	3.5
15/02/2017	0.59	7.30	8.01	6.33	163	35	0.15	2.70	135	50	0.08	3.2

Appendix 3. EEMS Volumes and Spectra

Raw Water

	Spectrum Number	Region I	Region II	Region III	Region IV	Region V
6/05/2015	a	2456	30184	337689	37553	703320
20/05/2015	b	3835	33781	378244	41544	842643
02/12/2015	c	933	26461	404072	37259	873156
25/11/2016	d	-1774	621	41101	3925	131319
6/01/2017	e	3801	22994	418872	33768	735673
11/01/2017	f	7619	22278	391625	30454	673531
19/01/2017	g	5188	21538	385465	29792	635242
31/01/2017	h	-903	15076	394358	26901	630278
15/02/2017	i	1991	17004	390181	27538	563146
13/04/2017	j	8558	43928	644153	53806	863846
28/04/2017	k	9005	39697	654494	56015	1011313



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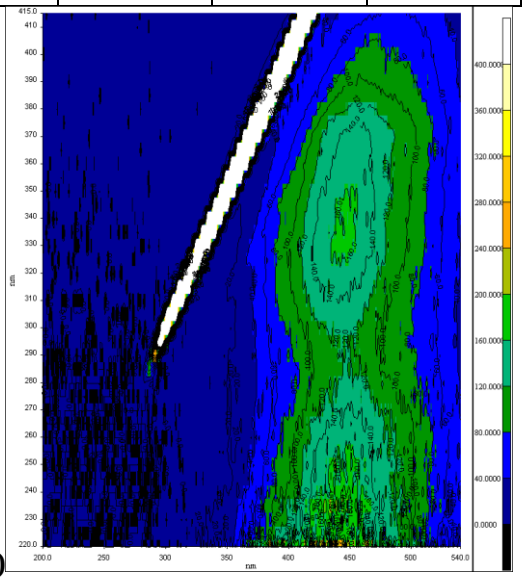

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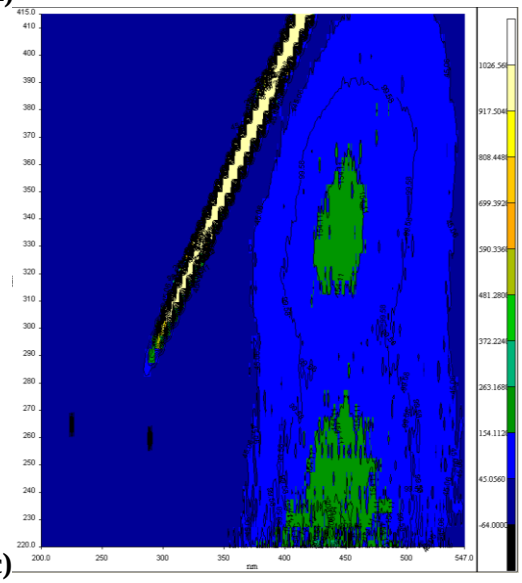

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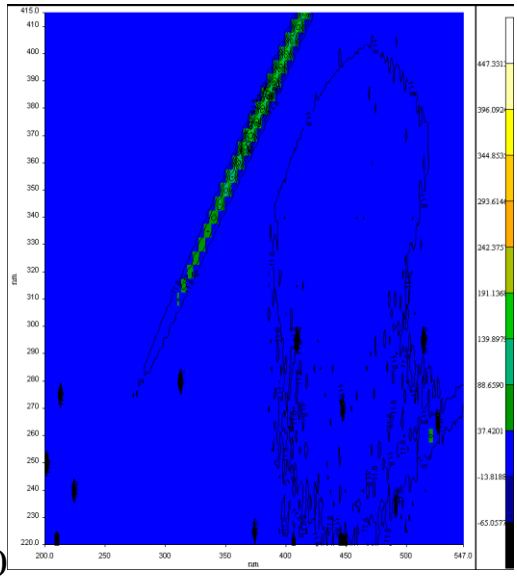

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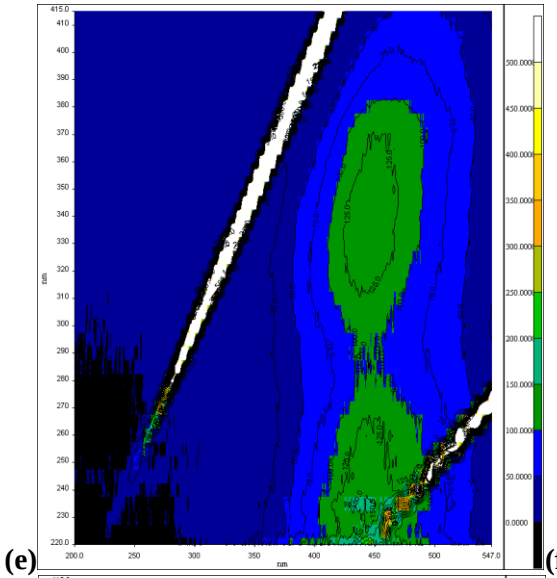
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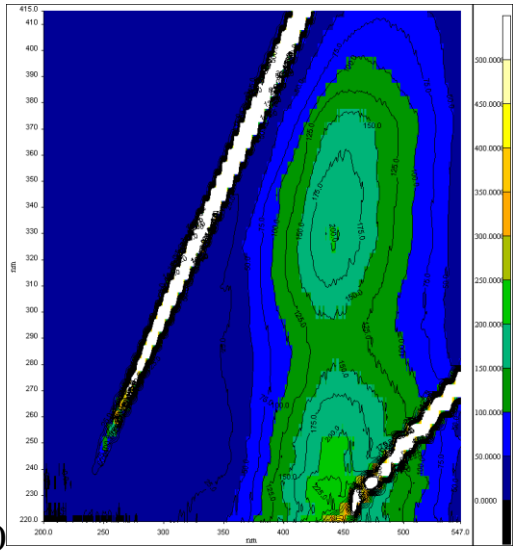
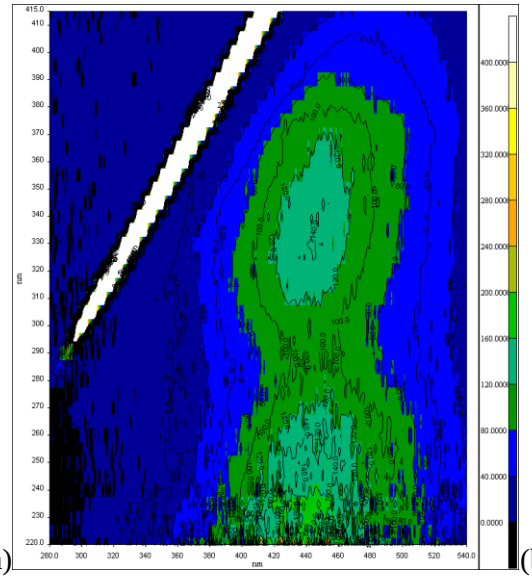
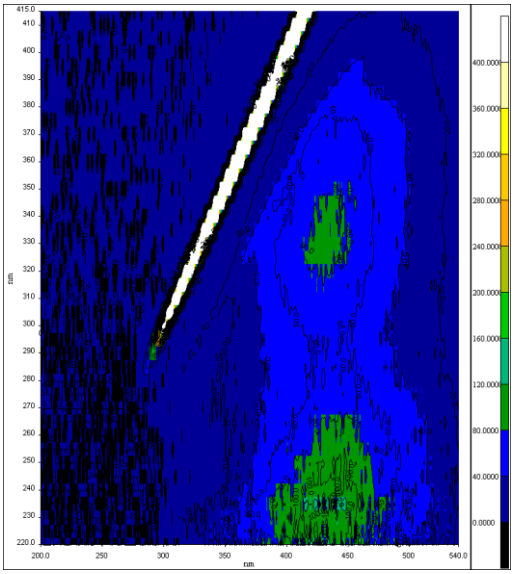
(f)
(g)
(h)
(i)
(j)

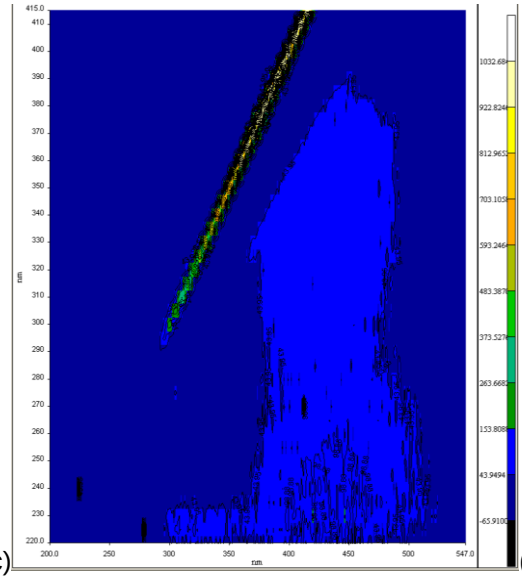
(k) 

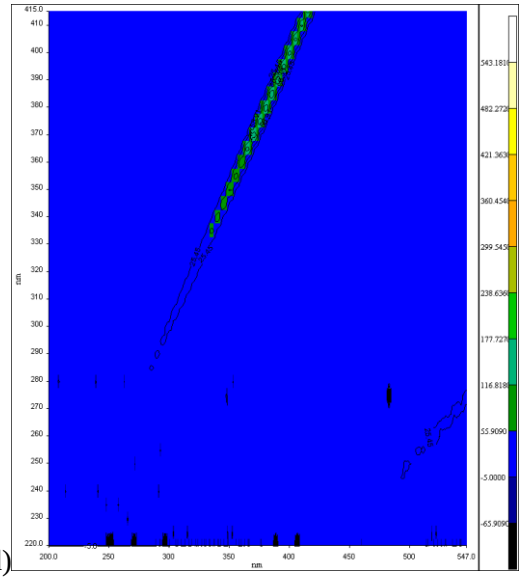
Water Treatment Plant

Date	Spectrum Number	Region I	Region II	Region III	Region IV	Region V
6/05/2015	a	11530	29962	179357	38690	345747
20/05/2015	b	4294	30174	218788	39044	400595
02/12/2015	c	17471	35003	212563	44500	391966
25/11/2016	d	-468	290	25054	3240	67428
6/01/2017	e	6713	26571	275045	32872	398341
11/01/2017	f	5342	27974	255921	32458	352708
19/01/2017	g	3594	25039	236064	29743	347196
31/01/2017	h	118	17259	194998	25527	290710
15/02/2017	i	-247	16617	188733	23146	266899
28/04/2017	j	6077	36588	340257	43910	460000

(a) 

(b) 

(c) 

(d) 

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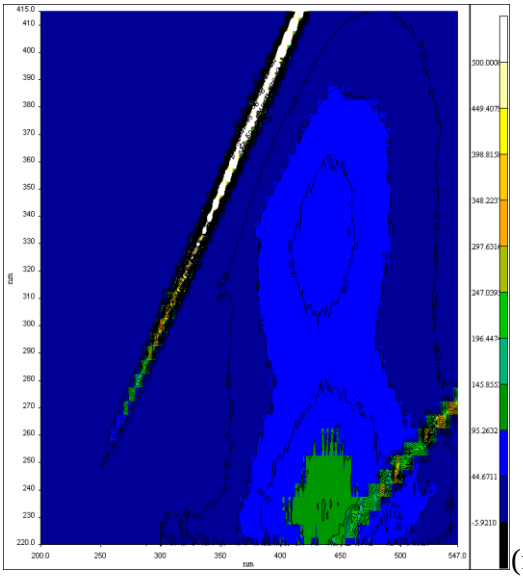

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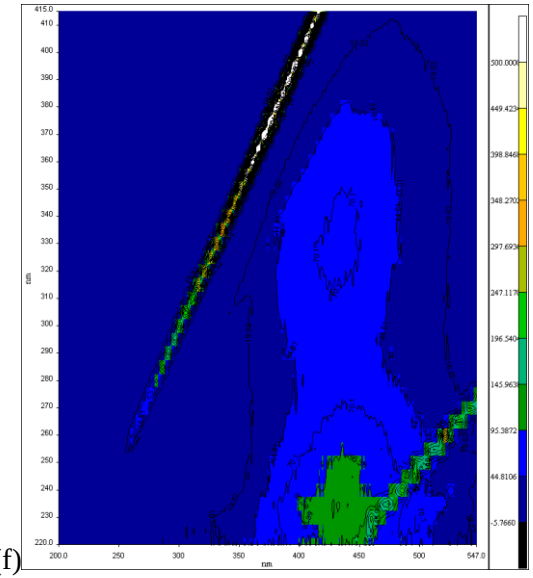

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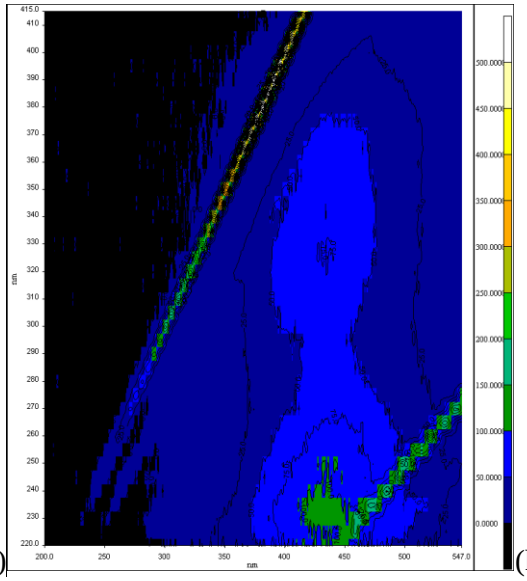

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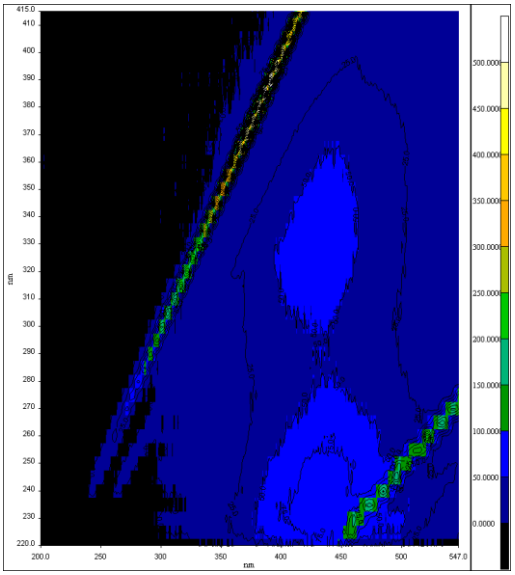

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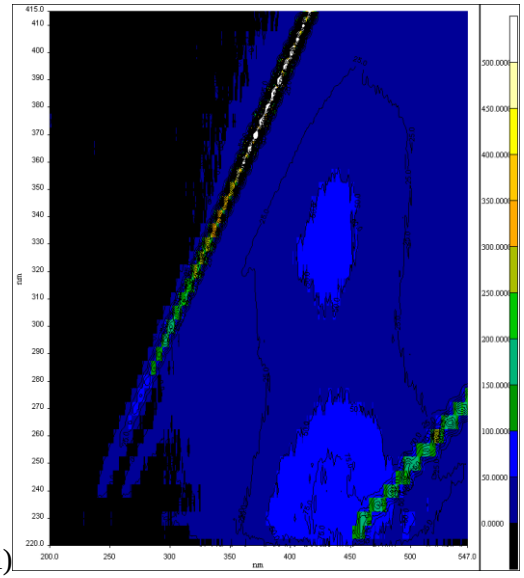

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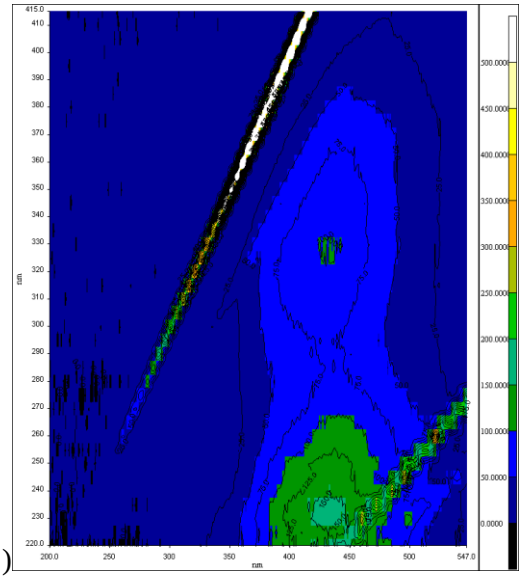
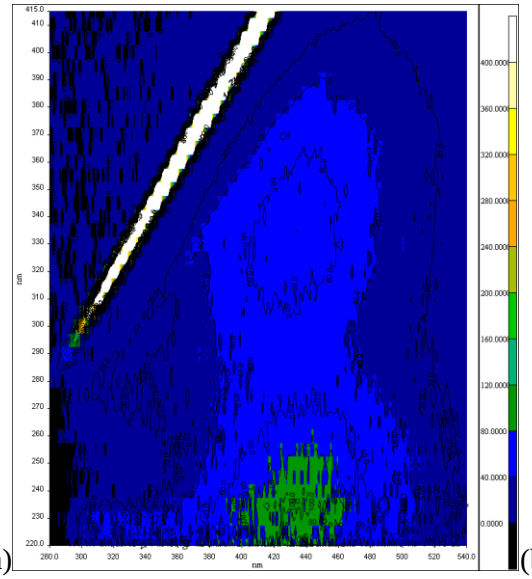


Aluminium Sulphate Jar Tests

Date	Spectrum Number	Region I	Region II	Region III	Region IV	Region V
6/05/2015	a	10068	29221	179511	38883	335131
20/05/2015	b	3425	28438	205195	37526	384095
25/11/2016	c	-2073	2849	19045	4055	40794
11/01/2017	d	9638	36349	435103	42875	508525
19/01/2017	e	10945	26603	240867	32437	367617
31/01/2017	f	-313	17205	210687	25973	331501
13/04/2017	g	2770	20976	269120	27952	246857
28/04/2017	h	19136	61182	604478	67152	756433

(a)



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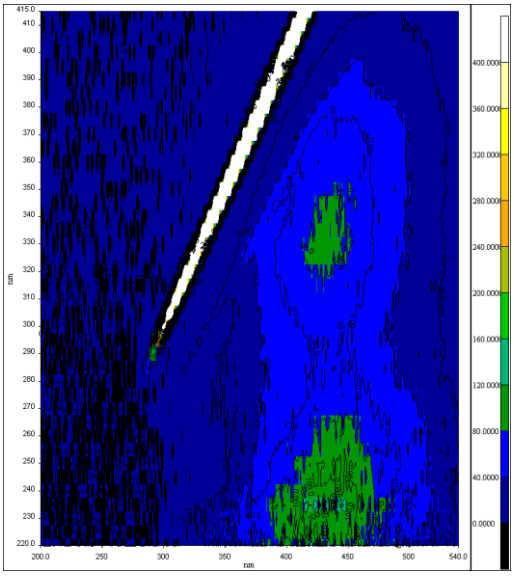

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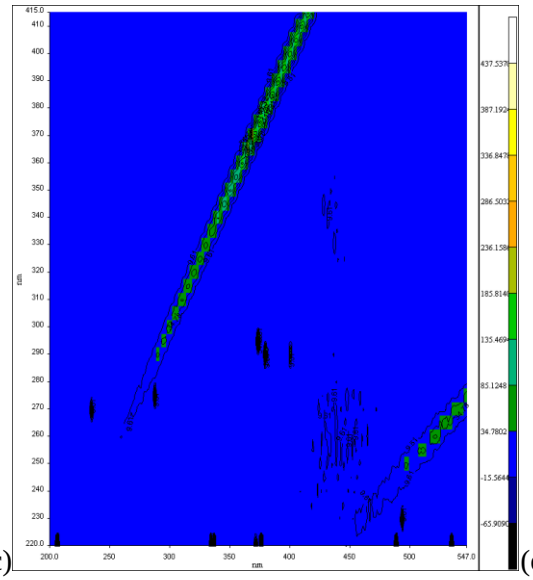

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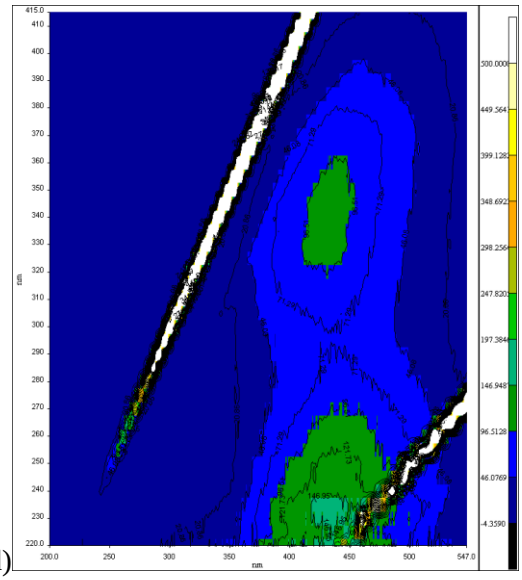

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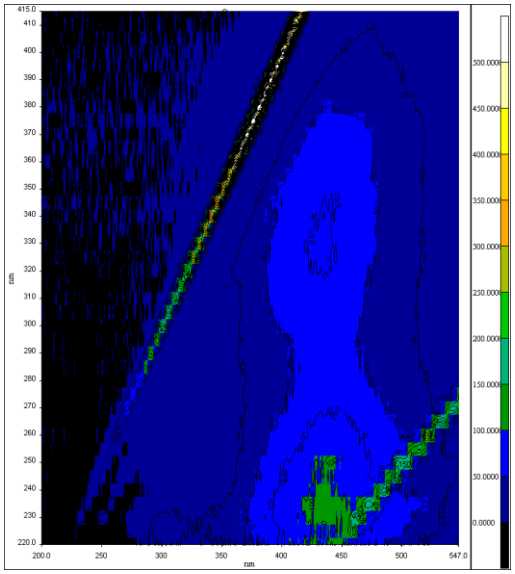

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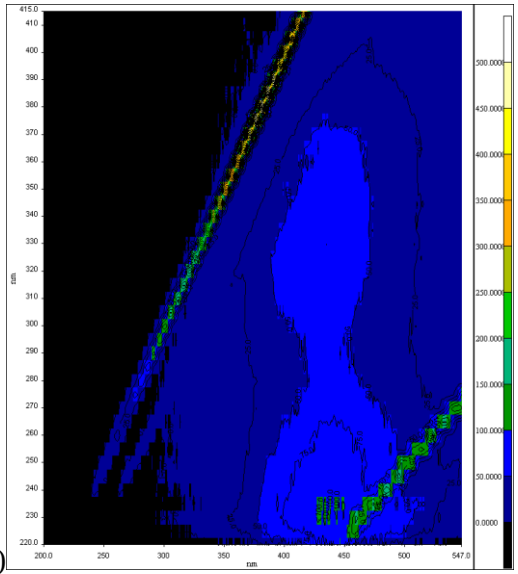

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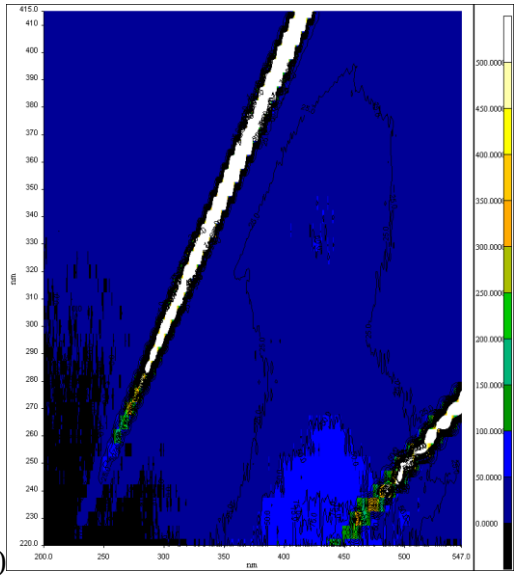

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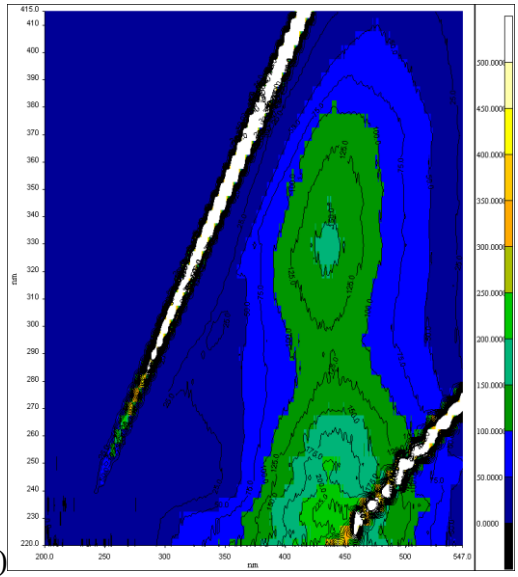
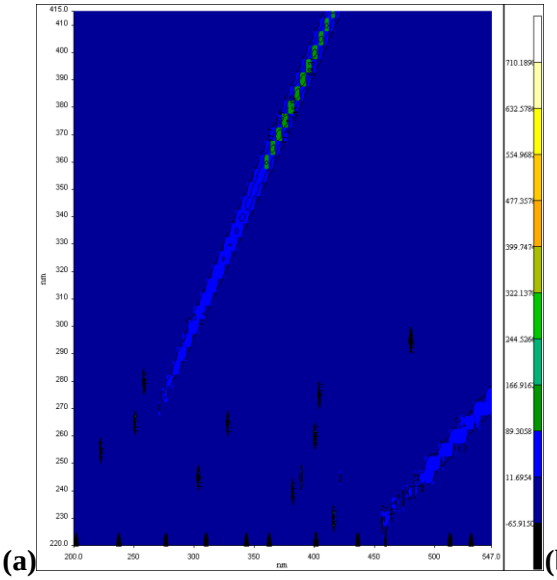


Ferric Sulphate Jar Tests

Date	Spectrum Number	Region I	Region II	Region III	Region IV	Region V
25/11/2016	a	-533	860	19069	1216	38970
6/01/2017	b	10215	27421	186532	29163	245312
11/01/2017	c	7703	19169	146505	22817	188078
19/01/2017	d	758	16707	147490	21474	190668
31/01/2017	e	-594	9871	111994	16491	149702
15/02/2017	f	1164	15936	163655	21526	215285
13/04/2017	g	1316	13587	124862	18291	140304
28/04/2017	h	5639	23968	356491	32960	263849



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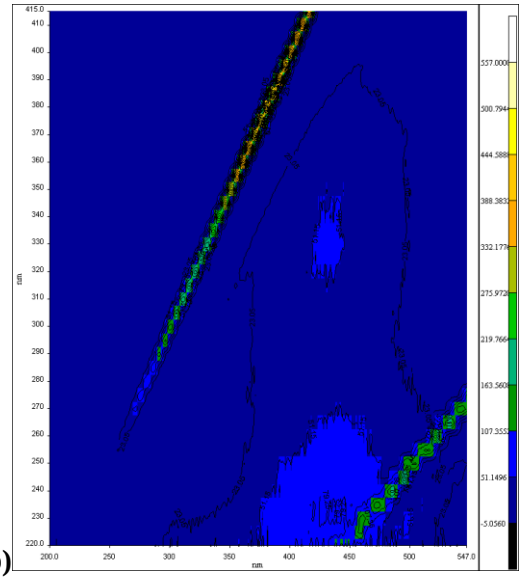

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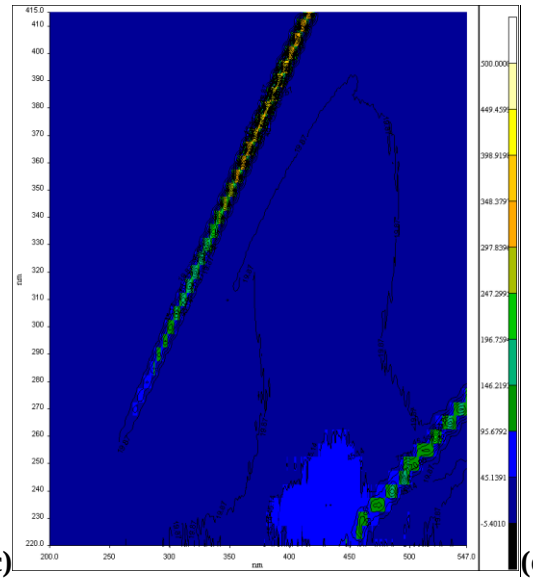

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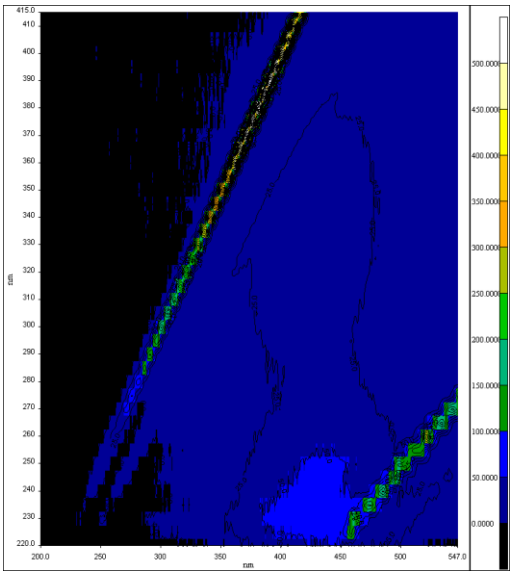

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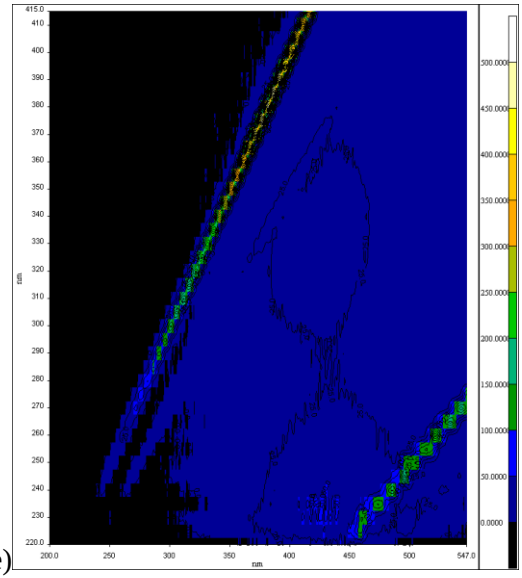
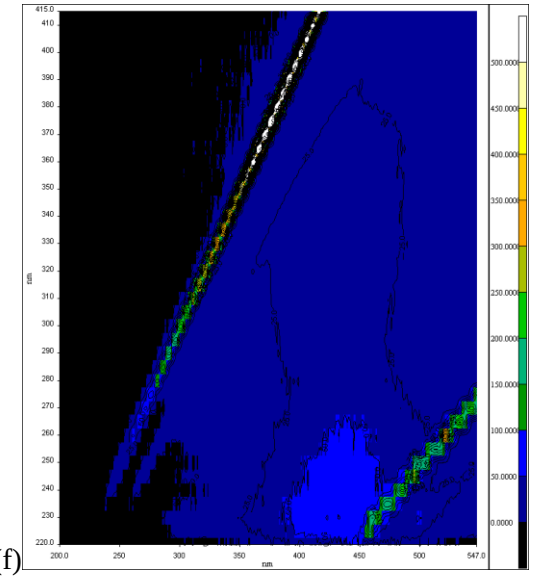
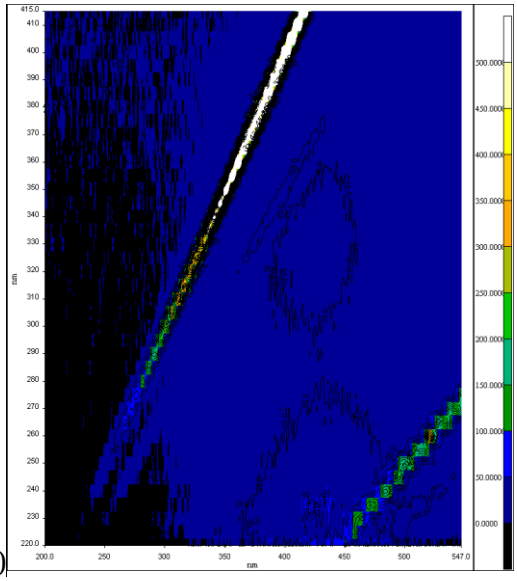
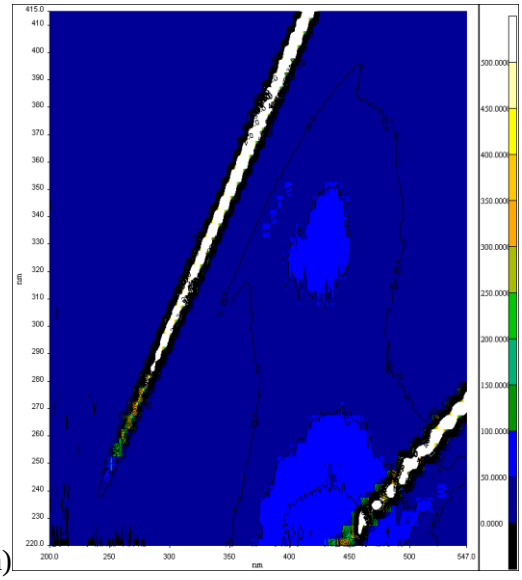
(e) 

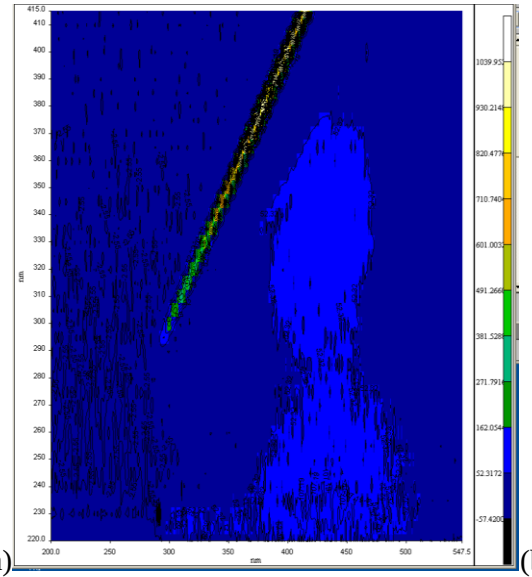
(f) 

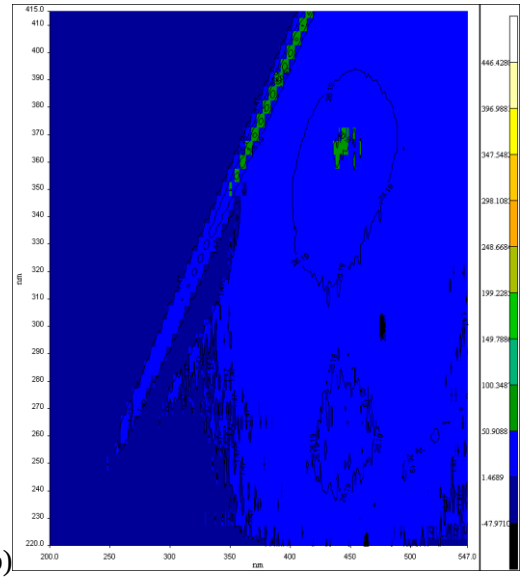
(g) 

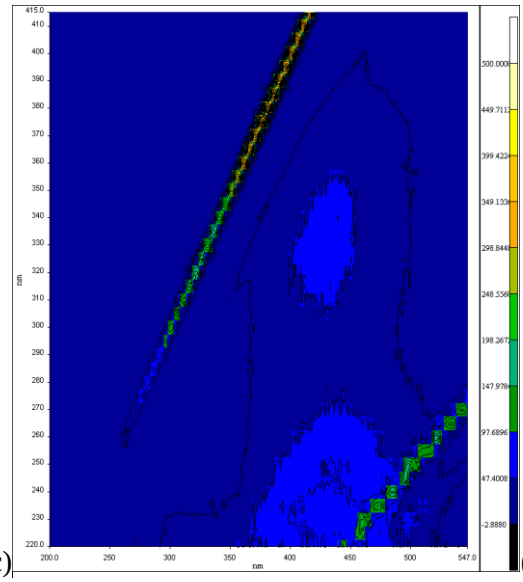
(h) 

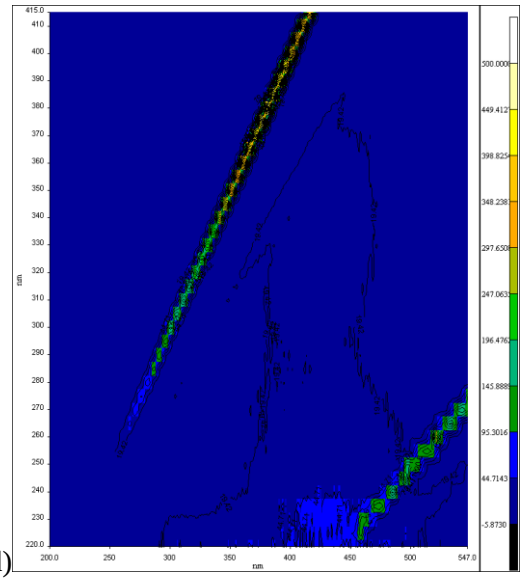
ACH Jar Tests

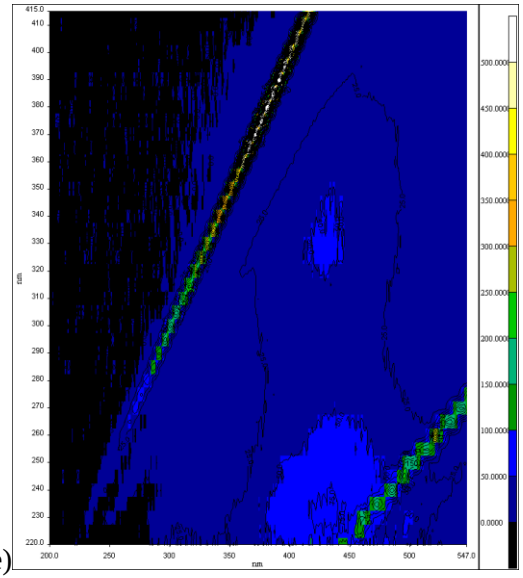
Date	Spectrum Number	Region I	Region II	Region III	Region IV	Region V
2/12/2015	a	12753	29832	199620	38491	348564
25/11/2016	b	-1550	1460	51885	6987	176289
6/01/2017	c	12239	27718	184251	30444	250020
11/01/2017	d	10162	22799	209710	28345	291218
19/01/2017	e	8210	22391	182472	26408	239179
31/01/2017	f	3253	17315	210342	24923	250602
15/02/2017	g	25196	20577	174932	29477	236029
13/04/2017	h	-1456	14407	169302	29141	359606
28/04/2017	i	6196	34685	333254	42328	424243

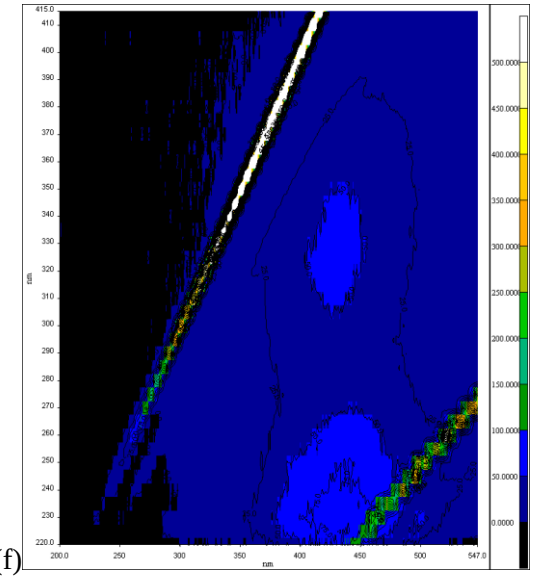
(a) 

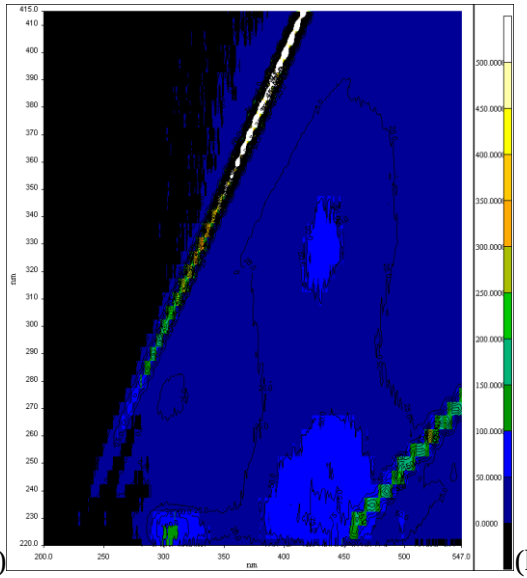
(b) 

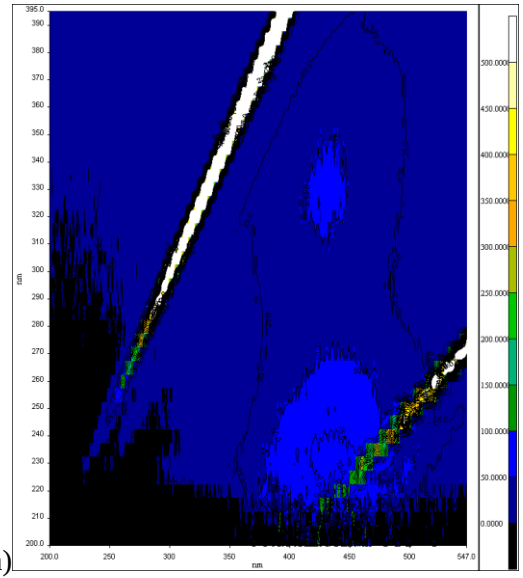
(c) 

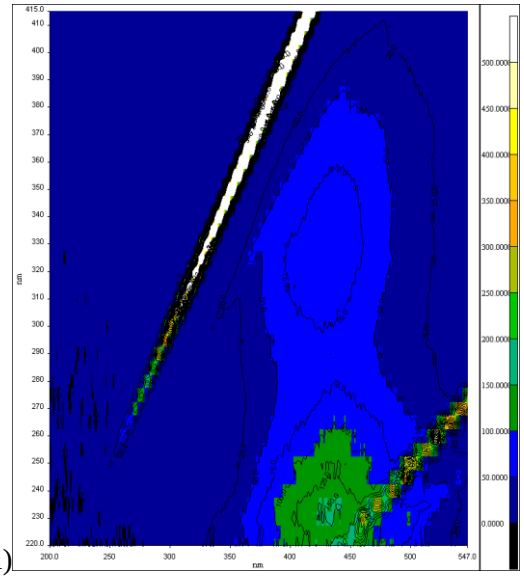
(d) 

(e) 

(f) 

(g) 

(h) 

(i) 

Appendix 4. DOC fractions associated with Liquid Chromatography Organic Carbon Detection

D-O-C LABOR

DOC | HOC* | CDOC

Approx. Molecular Weights in g/mol:
~1000 (see separate HS-Diagram)

>>20.000 | 300-500 | <350 | <350

	Dissolved	Hydrophob.	Hydrophil.	BIO-polymers				Humic Subst. (HS)				Mol-Weight	Position in HS diagram	Building Blocks + HS	LMW Neutrals	LMW Acids	Inorg. Colloid.	SUVA
	ppb-C	ppb-C	ppb-C	ppb-C	DON (Norg)	N/C	% Proteins in BIOpol.**	ppb-C	DON (Norg)	N/C	Aromaticity (SUVA-HS)	(Mn)	–	ppb-C	ppb-C	% DOC	SAC (m^{-1})	(SAC/DOC)
	% DOC	% DOC	% DOC	% DOC	–	–	–	% DOC	–	–	L/(mg*m)	g/mol	–	% DOC	% DOC	DOC	–	L/(mg*m)
Sample 1	4354	701	3653	323	42	0.13	39	967	69	0.07	3.31	219	A	1270	1079	14	1.06	1.08
Plant	100%	16.1%	83.9%	7.4%	–	–	–	22.2%	–	–	–	–	–	29.2%	24.8%	0.3%	–	–
Sample 2	2668	526	2142	176	n.q.	–	–	367	41	0.11	5.59	184	B	827	718	54	0.13	1.43
Ferr	100%	19.7%	80.3%	6.6%	–	–	–	13.8%	–	–	–	–	–	31.0%	26.9%	2.0%	–	–
Sample 3	3853	755	3098	250	7	0.03	9	575	31	0.05	1.53	193	C	1313	960	n.q.	0.14	0.83
Ach	100%	19.6%	80.4%	6.5%	–	–	–	14.9%	–	–	–	–	–	34.1%	24.9%	–	–	–
Sample 4	6469	628	5841	534	17	0.03	10	3428	170	0.05	3.08	182	D	674	1205	n.q.	1.09	2.32
Alum	100%	9.7%	90.3%	8.3%	–	–	–	53.0%	–	–	–	–	–	10.4%	18.6%	–	–	–
Sample 5	12599	1103	11496	1155	31	0.03	8	7721	301	0.04	4.59	624	E	1384	1236	n.q.	2.51	2.88
Raw	100%	8.8%	91.2%	9.2%	–	–	–	61.3%	–	–	–	–	–	11.0%	9.8%	–	–	–

LMW= Low-molecular weight

DON= Dissolved organic nitrogen

n.q.= not quantifiable (<1 ppb calculated)

n.m.=not measured

"Biopolymers"= Polysaccharides, Proteins, Aminosugars

"Building blocks"= Breakdown products of humics

"Neutrals" includes mono-oligosaccharides, alcohols, aldehydes, ketones

"Acids"= Summaric value for monoprotic organic acids <350 Da

Appendix 5. Taste and Odour Panel Data and analysis

Null Hypothesis: The odour of the data sample type of chemical used is independent of the odour in the jar test samples

Chi Squared Statistic: 7.46, p = 0.49

The count of odours detected by the panel from the jar tests compared to the expected values (in brackets)

	Chlorine	**Chemical**	**Earthy /musty**	**None**	**Other**	**Row Totals**
Aluminium sulphate	3 (2.46)	4 (5.33)	36 (31.97)	28 (29.10)	4 (6.15)	**75**
ACH	2 (1.77)	4 (3.84)	20 (23.02)	25 (20.95)	3 (4.43)	**54**
Ferric Sulphate	1 (1.77)	5 (3.84)	22 (23.02)	18 (20.95)	8 (4.43)	**54**
Column Totals	**6**	**13**	**78**	**71**	**15**	**183**

Null Hypothesis: The odours of the data samples from the WTP are independent of the odour of the data sample from the jar test samples

Chi Squared Statistic: 8.36, p = 0.08

The count of odours detected by the panel from the jar tests and the WTP compared to the expected values (in brackets)

	Chlorine	**Chemical**	**Earthy /musty**	**None**	**Other**	**Row Totals**
Jar tested samples	6 (4.69)	13 (14.75)	78 (85.80)	71 (66.36)	15 (11.40)	**183**
WTP samples	1 (2.31)	9 (7.25)	50 (42.20)	28 (32.64)	2 (2.32)	**90**
Column Totals	**6**	**13**	**78**	**71**	**17**	**183**

Null Hypothesis: The odours of the data samples from the final water samples (Euroa and Shepparton) are independent of the odour of the data sample from the jar test samples

Chi Squared Statistic: 182.41, $p < 0.00001$

The count of odours detected by the panel from the jar tests, the WTP, and the final water from Shepparton and Euroa compared to the expected values (in brackets)

	Chlorine	**Chemical**	**Earthy /musty**	**None**	**Other**	**Row Totals**
Jar tests	6 (30.08)	13 (16.94)	78 (70.32)	71 (55.92)	15 (9.74)	**183**
WTP	1 (14.79	9 (8.33)	50 (34.58)	28 (27.50)	2 (4.79)	**90**
Euroa final	14 (13.15)	10 (7.41)	31 (30.74)	20 (24.44)	5 (4.26)	**80**
Shepparton	50 (12.98)	8 (7.31)	7 (30.36)	13 (24.14)	1 (4.21)	**79**
Column Totals	**71**	**40**	**166**	**132**	**23**	**432**

Appendix 6. Triple Bottom Line Assessment Calculations

Economic Assessment

Operational costs	Base case	Aluminium sulphate	ACH	Ferric sulphate
Operational cost score	0	1	3	-4
Infrastructure program score	0	0	2	0
Total	**0**	**1**	**5**	**-4**
Ranking	**3**	**2**	**1**	**4**

Social Assessment

	Base Case	Aluminium Sulphate	ACH	Ferric Sulphate
Score based on the impacts to the community	0	0	3	2
Score based on the impacts to GVW staff	0	0	2	1
Score based on the impacts to the WTP operator	0	-1	-1	3
Total	**0**	**-1**	**4**	**6**
Ranking	**3**	**4**	**2**	**1**

Environmental Assessment

	Base Case	Aluminium Sulphate	ACH	Ferric Sulphate
Score based on landfill requirements	0	0	3	-1
Score based on CO_2 emissions	0	0	4	2
Total	**0**	**0**	**7**	**1**
Ranking	**3**	**3**	**1**	**2**

Triple Bottom Line Assessment

TBL assessment based on the weightings in Tables 5 and 6

	Base Case	Aluminium Sulphate	ACH	Ferric Sulphate
Triple Bottom Line Assessment	0	0	5.25	1
Financial bias	0	0.25	5.25	-0.25
Environmental bias	0	0	5.75	1
Social bias	0	-0.25	5	2.25